LEAN LOGISTICS

High-Velocity Logistics Infrastructure and the C-5 Galaxy

Timothy L. Ramey

Prepared for the United States Air Force

Project AIR FORCE

RAND

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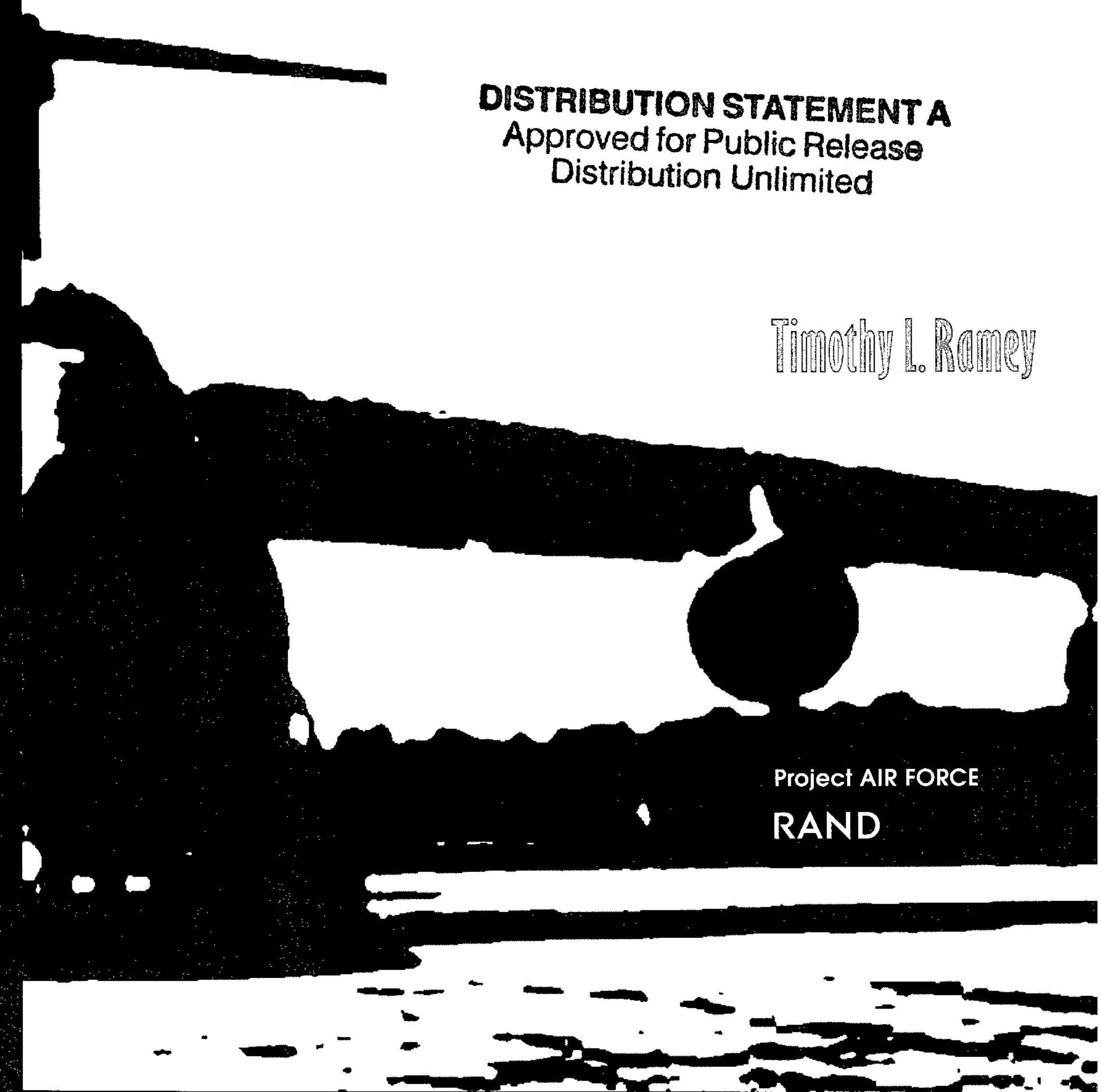

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PREFACE

As part of a body of research defining and evaluating the concept of Lean Logistics for the U.S. Air Force, this report considers the effects on operation of the C-5 Galaxy of radically reducing the time required to move and repair components of that airlift aircraft. The analysis uses Air Force data to drive simulations of C-5 logistics operations and considers peacetime flying programs.

This research was conducted in the Resource Management and System Acquisition program of Project AIR FORCE. It is one element of the Logistics Project, sponsored by Headquarters, United States Air Force (AF/LG). Headquarters, Air Mobility Command (AMC/LG), and Air Force Materiel Command (AFMC/XP) provided important assistance in ensuring the successful design and execution of this project. This report should be of interest to persons concerned with the logistics support of airlift aircraft and, particularly, to logisticians involved in the management of aircraft recoverable spare parts.

Project AIR FORCE

Project AIR FORCE, a division of RAND, is the Air Force federally funded research and development center for studies and analyses. It provides the Air Force with independent analyses of policy alternatives affecting the development, employment, combat readiness, and support of current and future aerospace forces. Research is performed in three programs: Strategy and Doctrine, Force Modernization and Employment, and Resource Management and System Acquisition.

CONTENTS

FIGURES

TABLES

SUMMARY

The study reported here is part of a body of research developing the concept of Lean Logistics for the U.S. Air Force. It considers the effect of radically shortened spare-parts transportation and repair times on performance of the C-5 Galaxy airlift aircraft. Similar changes in the commercial manufacturing sector have been shown to improve supplier responsiveness and to significantly reduce in-process inventory requirements.

A simulation model of C-5 fleet operation and support was constructed for this study using the latest version of RAND's Dyna-METRIC.[1] That model was reviewed by Air Mobility Command (AMC) and was validated by comparing simulated performance of the C-5 fleet under today's logistics infrastructure with historical performance as reported by AMC.

The model was then used to compare simulated performance under the current ("standard") logistics infrastructure with simulated performance under a high-velocity infrastructure (HVI) over a variety of scenarios and assumptions. Such an infrastructure is an important element of the Air Force's emerging strategy called *Lean Logistics.* A provider of goods or services that takes less time to respond to a

[1]Developed by RAND in the mid-1980s, Dyna-METRIC is an analytic tool for gaining an understanding of the implications of logistics-system alternatives for military capability. It has seen wide application within the Air Force. Two versions of Dyna-METRIC are in common use: an older analytic version (Version 4), which uses mathematical modeling (Isaacson, Boren, Tsai, and Pyles, 1988); and a more recent version (Version 6), which uses Monte Carlo–based, discrete-event simulation (Isaacson and Boren, 1993). Version 6 (the simulation version) was used in this study.

consumer's needs tends to be affected less by variations in consumer demands, to be more effective in the face of production and demand uncertainties, and to need less work-in-process inventory. A high-velocity logistics infrastructure emphasizes speed of processing over mass of inventory.

In the high-velocity infrastructure considered in this study, we assumed transportation times of 1 or 2 days (achieved, for example, through the use of commercial express carriers) and depot-level component repair-flow times that approximate hands-on repair times (on average, about 7 days). The current infrastructure has transportation times of around 17 days and depot repair-flow times averaging 54 days. Taking into account the availability of base-level repair capabilities, we calculated that the full time required by the current infrastructure to turn a broken part into one ready for use again is, on average, 67 days.

Scenarios considered in this study include changes in assumed logistics factors (such as part failure rates), assumed operating program (number of missions flown), availability of transportation, and success of Lean Logistics implementation. Several excursions also consider variations in the underlying logistics infrastructure.

RESULTS FOR A BASELINE SCENARIO

- Simulation of the standard-infrastructure model approximates AMC experience.
- Performance of the HVI model approximates performance of the standard-infrastructure model.
- Inventory requirement is reduced under the HVI, which could lead to budgetary savings over time.
- Issue effectiveness will decline under an HVI.
- The use of cannibalization actions and other management adaptations should be reduced under an HVI; such actions should be more effective than they are currently.

From this study, we found that, across a wide range of conditions and circumstances, a high-velocity infrastructure would provide C-5 performance that is the same as or better than that provided by the

current infrastructure. A high-velocity infrastructure requires only one-sixth the inventory having one-third the value of the inventory required by the current infrastructure. Reductions in inventory requirements could eventually reduce outlays ascribable to C-5 inventory turnover by as much $32 million a year. As an additional benefit, such radical reductions in pipeline inventory might also lead to reductions in management and information-systems overhead.

RESULTS FOR ALTERNATIVE SCENARIOS

- HVI is substantially less affected by spares acquisition lead times.
- HVI cushions the debilitating effect of variability in demand rates.
- Small C-5 operating tempo surge has little effect on either infrastructure.
- HVI would support a major operation substantially better than does the current infrastructure.

A high-velocity logistics infrastructure would perform better than the current infrastructure under most of the stressing scenarios examined in this study. Generally, it would cushion the effects of uncertainty in the logistics system and its environment. However, such a cushioning effect appears to be more limited for the C-5 than we anticipate for fighter and bomber aircraft. In particular, there appears to be limited opportunity for improved logistics performance at en route locations, which support over 60 percent of C-5 activity but have very little AMC supply presence and maintain stock for only a few hundred out of nearly 2,000 major reparable line items on the C-5.

RESULTS OF SENSITIVITY ANALYSES

- A transportation cutoff in the continental United States (CONUS) would slow—but not cripple—an HVI. The standard infrastructure would take much longer to recover from such a cutoff.
- HVI would make better use of current assets.

- Uncoordinated implementation of Lean Logistics would degrade performance under the HVI; the transition period will require management attention.
- Priority distribution may remain a useful management adaptation, but intensively managed forward stocks (i.e., FSLs) may not be as valuable under an HVI as under the current infrastructure.

A high-velocity infrastructure would appear to be no more vulnerable to unexpected failures than would the current infrastructure. For example, it would suffer no greater degradation from a CONUS–wide transportation cutoff than would the current infrastructure, but would recover from such a cutoff considerably faster once transportation had been restored. The risk to the Air Force that performance could not be sustained if inventory levels were reduced to Lean Logistics levels *before* a high-velocity infrastructure has been fully implemented also appears to be small. Because inventories would be reduced, careful management of those inventories could protect the Air Force from the potential for diminished performance. Although the full benefits of a high-velocity infrastructure might not be realized, viability of the logistics system would not be endangered.

CONCLUSIONS

Major findings of this study may be summarized as follows:

- C-5 performance would be improved by a high-velocity infrastructure, over a broad range of scenarios and assumptions.
- AMC's forward supply system (FSS) already conforms to our expectations for a high-velocity infrastructure fairly well; CONUS and depot portions of the infrastructure would benefit most from the changes examined here.
- Inventory reductions could reap moderate savings, but only over several years' time.
- Different weapon systems will respond differently to implementation of Lean Logistics initiatives. Generalizing specific results of this study to other weapon systems may be problematic.

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Reviewers Chris Hanks and Paul Killingsworth made important suggestions, most of which I have faithfully implemented here. Any remaining errors are, of course, my own.

ACRONYMS AND TERMS

2LM	Two-Level Maintenance—an Air Force logistics initiative limiting repair activity for some parts to the wholesale echelon
AAM	Aircraft availability model—generally, an approach to modeling spares requirements that ties the requirement to the aircraft availability that might eventuate; more specifically, the system of software embedded in D041 and used to compute requirements for safety stock of selected recoverable items (see *D041; requirement*)
AB	Air base
ACC	Air Combat Command
AETC	Air Education and Training Command
AFB	Air Force base
AFMC	Air Force Materiel Command
AFRES	Air Force Reserve
ALC	Air Logistics Center
AMC	Air Mobility Command
ANG	Air National Guard
ARB	Air Reserve component base
asset	as used in this report, a physical item; compare the term *part,* which usually refers to a class of essentially identical assets identified by an NSN

AWP	Awaiting parts—items in repair may be held up when the components necessary to complete the repair are not available; they are said to be in AWP status
backorder	an unfilled demand on the supply system for an asset
backshop	a repair facility collocated with a flight line
beddown	the placement of specific aircraft at specific locations
BP-15	Budget program 15—a category of appropriated funds allocated to recoverable aircraft replenishment spares
carcass	a reparable item (*asset*) that has been damaged or is otherwise in need of repair
CIRF	Centralized intermediate repair facility—a modeling element in Dyna-METRIC representing the second echelon within a multiechelon logistics system
consumable	an item that is directly consumed in the course of its use or that is not repaired for reuse when damaged or worn (compare *reparable*)
contingency	a military action of substantial risk to personnel and equipment and having uncertain outcome
CONUS	Continental United States—the 48 contiguous states
CRAF	Civil Reserve Air Fleet—a program through which commercial air carriers agree to make airlift and passenger capacity available for military use in times of need; CRAF may be activated by the President in several stages
D041	AFMC's system for computing requirements for aircraft recoverable spares, formally entitled the *Recoverable Consumption Item Requirements System*
demand	a request by a user of the supply system for a particular item (*asset*); such a request is usually manifested in a requisition

depth	in reference to inventory levels, the number of assets of a given type (*part*) that are present in the inventory (compare *range*)
depot	a supply, repair, or maintenance facility and supporting organization at the *wholesale* echelon within Air Force logistics
DLA	Defense Logistics Agency
DRIVE	Distribution and Repair In Variable Environments—a system of software for prioritizing the repair of aircraft components and allocating serviceable assets to bases
Dyna-METRIC	Dynamic Multi-Echelon Technique for Recoverable Item Control—a logistics modeling and simulation tool developed by RAND and used throughout the Air Force; in two versions—an analytic (mathematical) version and a Monte Carlo discrete-event simulation version—the latter was used in this study
echelon	any of several organizational levels within the logistics system; in general, the Air Force operates a multiechelon logistics system consisting of flight-line logistics, intermediate logistics, depot-level logistics, and contractor support
en route	(1) airlift aircraft that are in the process of carrying out an airlift mission are said to be en route; (2) locations away from home base to which airlift aircraft carry cargo are said to be en route locations
FCFS	First come–first served—a scheduling strategy in which the oldest task or item awaiting service is dealt with first; under some conditions, this strategy is probabilistically equivalent to a strategy of randomly selecting the next task or item for service (which is a much simpler strategy to simulate than keeping track of the arrival times of each individual task or item)

FMC	Fully mission capable—the status of an aircraft that is capable of performing all of its assigned missions (compare *PMC, NMC*)
forward	(1) movement of assets toward operating locations (bases) is said to be forward movement (compare *retrograde*); (2) locations nearer a theater of operation are said to be forward locations
FSC	Federal Supply Classification—a systematic way of grouping parts into classes to facilitate accomplishment of supply management objectives for all items in the inventory; one component of the national stock number (*NSN*)
FSL	Forward supply location—part of AMC's forward supply system; the FSLs are located overseas and provide supply support to en route locations
FSS	Forward supply system—a supply system operated by AMC that supports its en route locations
grounded	an aircraft that is unable to fly an assigned mission, usually because of supply or maintenance shortages, is said to be grounded
hands-on time	as used in this report, the time an asset undergoing repair spends actually being worked on
home base	the base to which aircraft are assigned and at which they are usually located; when not at home base, aircraft are either en route or at a depot being overhauled
HVI	High-velocity infrastructure—a logistics infrastructure in which speed of processing is deliberately favored over mass of inventory as a systemic management technique; the HVI explored in this study would radically reduce transportation and depot repair times
IAP	International airport
ICAO	International Civil Aviation Organization
indenture	the physical relationship of items as assemblies, subassemblies, components, and so forth

infrastructure	the collection of installations, facilities, and their interconnections used to support military operations
inventory level	as used in this report, a *level* is the number of assets of a part that have been assigned to a location as a result of a requirements-computation process, whether or not such assets can or will be located there; a level often includes assets that would not normally be found at the location because they would be in transit, and may include (hypothetical) assets that the Air Force has insufficient funding to procure (see *requirement*)
issue	in reference to inventory and stock control, the act of transferring an asset from the supply system to a technician; stock is *issued* for use in repair
issue effectiveness	a supply system measure of merit—the proportion of times that the supply system has a part to issue at the time a technician makes a request for that part
IWSM	Integrated weapon system management—a formal part of Air Force acquisition reform instituted in 1992; a single system program director (*SPD*) is designated to be responsible for each weapon-system acquisition program from inception through disposal
JIT	Just in time—a manufacturing and supply approach that strives to have a component or commodity available to the next step in a process no earlier than it has to be to serve its need
lateral support	support that one base provides for another, usually on a quid pro quo basis
Lean Logistics	a program of Air Force logistics initiatives derived from modern business practices and focused on meeting the primary challenges that have emerged since the end of the Cold War: increasingly unpredictable operations needs and rapidly falling logistics budgets

level	as used in this report, a *level* is the number of assets of a part that has been assigned to a location as a result of a requirements-computation process, whether or not such assets can or will be located there; a level often includes assets that would not normally be found at the location because they would be in transit, and may include (hypothetical) assets that the Air Force has insufficient funding to procure (see *requirement*)
line item	a type of asset; a part, having a unique NSN (see *part;* compare *asset*)
LRU	Line-replaceable unit—a reparable item that can be replaced on the flight line
MC	Mission capable—the status of an aircraft that can perform some or all of its assigned missions; may be *FMC* or *PMC* (compare *NMC*)
MDS	Mission design series—a designation of weapon systems that groups together systems with substantially similar logistics support requirements (*C-5B* is an MDS and labels a portion of the C-5 fleet in which each aircraft has essentially the same configuration)
MESL	Minimum essential subsystem list—a list of those aircraft subsystems that are essential to the aircraft's operation or to a specific mission; that is, those subsystems without which a particular mission cannot be performed
mission	(1) a particular military action; for the C-5, a mission consists of transporting cargo or personnel among two or more locations (hence, a mission subsumes several *sorties*); (2) the type of military action for which a system is intended or is typically used (the mission of the C-5 is airlift of outsized cargo)

Monte Carlo	an approach relating to the use of random sampling techniques to obtain approximate solutions to mathematical or physical problems; simulations such as Version 6 of Dyna-METRIC use such random sampling techniques
NIIN	National item identification number—a designator assigned to an individual item of supply that differentiates it from all other items of supply; one component of the national stock number (*NSN*)
NMC	Not mission capable—the status of an aircraft that is incapable of performing any of its assigned missions; may be NMCS (due to *supply* delays), NMCM (due to *maintenance* delays), or NMCB (due to *both*) (compare *FMC, PMC*)
NRTS	Not reparable this station—a condition in which no adequate repair action can be taken at the current echelon of repair, perhaps because repair is not authorized or from lack of authorized equipment, personnel, or component parts
NSN	National stock number—a compound designator assigned to an individual item of supply that differentiates it from all other items; composed of the federal supply classification (*FSC*) for the part, the national item identification number (*NIIN*) for the part, and a material management code
OIMDR	Organization- and intermediate-level demand rate—a measure of supply activity generated against an individual line item by organization-level users (air wings) and intermediate-level users (PSPs, in the case of the C-5); excludes demands arising at the depot level
OST	Order-and-ship time—the time delay between when an order is placed with the wholesale portion of the supply system (the depots) and when the ordered part arrives ready for use, assuming that one part is available for issue at the wholesale level

PAA	Primary aircraft authorized—aircraft authorized to a command for the performance of its operational missions, including test and training requirements (actual aircraft in inventory may be less)
PAF	Project AIR FORCE—a division of RAND; the Air Force federally funded research and development center for studies and analyses
part	a type of component; each part has a unique NSN (see *line item*; *NSN;* compare *asset*)
PGMSEL	a selection field in the D041 database signifying the basis of accounting for demands (e.g., a value of 1 signifies that demands are counted per 100 aircraft flying hours)
pipeline	(1) the channel of support by which materiel flows between providers and users; (2) the corpus of assets found in that channel of support; (3) the length of time it takes an asset to travel through such a channel (to "shorten the pipeline" is to reduce that length of time)
PMC	Partially mission capable—the status of an aircraft whose ability to perform one or more of its assigned missions is degraded; may be PMCS (due to *supply* delays), PMCM (due to *maintenance* delays), or PMCB (due to *both*) (compare *FMC, NMC*)
POS	Peacetime operating stock—the level of stocks deemed to be necessary for a unit to perform its primary peacetime mission (compare *RSP*)
program	(1) a *flying* program is a planned sequence of missions to be flown over a fixed period of time; (2) a *computer* program is a sequence of instructions through which data are manipulated
PSP	Primary supply point—part of AMC's forward supply system; each PSP serves as a supply-and-repair center for a number of forward supply locations (see *FSS, FSL*)

QPA	Quantity per application—the number of a given part to be installed on an aircraft or on the part's next-higher assembly
RAND	a private, nonprofit corporation founded to further scientific, educational, and charitable purposes, all for the public welfare and security of the United States of America
range	in reference to inventory, the number of line items (*parts*) present in the inventory (compare *depth*)
RBL	Requirements-Based Leveling—an approach for computing the level of stocks to be allocated to operating locations (see *requirement*)
reparable	an item that, if broken or worn, could be repaired (in some contexts, also called an *exchangeable* component or a *recoverable* component) (compare *consumable*)
requirement	in reference to inventory, the amount of stock needed at a location to support an assumed operating tempo, usually including a safety margin that protects the location from uncertainty in the rate of demands for parts; the requirement may exceed the amount of inventory owned by the Air Force (see *level*)
retail	portions of the logistics system under the control of the operating commands are referred to as *retail logistics* (compare *wholesale*)
retrograde	movement of assets away from operating locations (bases) is said to be retrograde movement (compare *forward*)
route	a complete path, from point of origin to final destination; often made up of several *segments*
RSP	Readiness spares package—a package of depot-level reparable spare parts sized to sustain planned contingency operations, without resupply, for a specified period of time; part of war reserve materiel (compare *POS*)

SA-ALC	San Antonio Air Logistics Center—a part of the Air Force wholesale (depot) system; the C-5 SPO was located here during this study
SBSS	Standard Base Supply System—the standard supply accounting system for retail echelons
segment	(1) one portion of a route flown by an aircraft, usually extending from one airbase to the next airbase (see *sortie*; compare *route*); (2) similarly, one portion of a pipeline [see *pipeline (1)*]; (3) within AMC, a portion of an RSP specifically designated to support a particular (hypothetical) need, usually sized to support a particular number of landings per month (see *RSP*)
serviceable	an asset that is in operable condition; that is, an asset that either is or could be installed for use (compare *carcass*)
SOR	Source of repair—wholesale (i.e., depot or contractor) location at which a part is repaired (compare *SOS*)
sortie	flight of a single aircraft from takeoff until landing [see *segment (1);* compare *mission*]
SOS	Source of supply—wholesale (i.e., depot or contractor) location at which a part is managed within the supply system; the SOR and SOS are often, but not always, different organizations at the same location (compare *SOR*)
SPD	System program director—the individual with overall responsibility for the management of a weapon system such as the C-130, F-15, or B-52
SPO	System program office—the office of the program director and the single point of contact with industry, government agencies, and other activities participating in the system acquisition process
SRU	Shop-replaceable unit—a reparable item that can be replaced only in a repair shop (usually a component of an *LRU*)

TACC	Tanker Airlift Control Center—a command-and-control entity within AMC, exercising overall operational control of the air mobility system
two-level maintenance	an Air Force logistics initiative limiting repair activity for some parts to the wholesale echelon (sometimes abbreviated as *2LM*)
UMMIPS	Uniform Materiel Movement and Issue Priority System—a Department of Defense–wide system established to ensure that materiel movement requirements are processed in accordance with the mission of the requiring activity and the urgency of need, and to establish maximum uniform requisition processing and materiel movement standards
USAF	United States Air Force
USTRANSCOM	U.S. Transportation Command—the Department of Defense organization charged with responsibility for strategic lift of military assets during contingency operations
VTMR	Variance-to-mean ratio—the unbiased estimator of the variance of a process divided by its mean
weapon system	a single combat instrument that incorporates in itself assemblies and components sufficient to conduct or support military operations (for example, the C-5 Galaxy airlift aircraft)
wholesale	portions of the logistics system not under control of the operating commands are referred to as *wholesale* logistics (including depot-level supply and repair, transportation, and contractor support) (compare *retail*)
WSMIS	Weapon System Management Information System—an automated information management system that assesses the Air Force's capability to go to war, sustain combat operations at desired levels, and improve combat capabilities through development of get-well plans for readiness and sustainability problems

WUC	Work unit code—an alphanumeric designator used in aircraft maintenance to identify a maintainable item on an aircraft.

Chapter One

INTRODUCTION

As a major outgrowth of RAND research into the applicability of modern business practices to Air Force logistics operations, in 1993 the Air Force established a program of logistics improvements called *Lean Logistics.* Lean Logistics updates Air Force logistics operations by applying technology and management innovations that have proved effective in the commercial world, are relevant to the central supply problems of the Air Force, and are affordable. Lean Logistics is an attempt to replace a decades-old logistics system with one that is state of the art.[1] It draws on an integrated set of business innovations termed "lean production" (Womak, Jones, and Roos, 1990).

In commercial practice, innovations in lean production reach far beyond the manufacturing floor. As envisioned and implemented in industry, lean production affects all processes related to a product throughout its life cycle: from initial design, to production and distribution, and on into continuing engineering support. Likewise, Lean Logistics is expected to affect all aspects of Air Force operation and support, and ultimately to be implemented throughout the Air Force.

An important element of Lean Logistics is a *high-velocity infrastructure:* A provider of goods or services that takes less time to respond to a consumer's needs tends to be less affected by variations in consumer demands, to be more effective in the face of production and demand uncertainties, and to need less work-in-process inventory.

[1]See Pyles et al. (forthcoming) for RAND's original vision of Lean Logistics and USAF (1995) for a discussion of Air Force Lean Logistics efforts.

A high-velocity logistics infrastructure emphasizes speed of processing over mass of inventory. Whereas today it takes, on average, 60 to 90 days for Air Force logistics processes to turn a broken reparable component into one ready for issue, a high-velocity infrastructure might produce that repaired component in 5 to 10 days.

Emphasizing speed over mass is an approach that has become feasible and wise for the Air Force, given the shift in the relationship between the cost of transportation and the cost of inventory. On the one hand, rapid, assured transport is now readily available from commercial express carriers. On the other hand, the 1993 inventory of aircraft reparable parts (March 1993 D041) contains over 10 times as many line items with a value exceeding $5,000 as were found in the 1953 inventory of all aircraft spare parts (Brown, 1956; adjusted to 1993 dollars).[2] More important, industry experience with similar logistics changes suggests that a high-velocity infrastructure would be better able to accommodate changes in consumer-demand patterns. This promise, of improved performance in the face of uncertainty, has been the driving force behind RAND's pursuit of Lean Logistics.

In 1992, the Air Force requested that RAND undertake a study of the way Lean Logistics principles might affect operational performance of its fleets; in particular, it requested a study of the C-5 Galaxy. In the study reported here, we have used the C-5 as an analytic test bed to extend RAND and Air Force thinking about Lean Logistics and especially about high-velocity infrastructures. We have evaluated the effect a high-velocity infrastructure may be expected to have on C-5 operations and readiness.

This chapter briefly describes results of preliminary, exploratory research into commercial business practices that might benefit the Air Force and that served to motivate Air Force and RAND interest in Lean Logistics. It then introduces the C-5 Galaxy and describes the

[2]In 1993, 38,834 (of 110,503) line items in the D041 database had a replacement value of $5,300 or greater. Brown (1956) reports that 3,400 (of 383,100) line items in the *USAF Worldwide Stock Balance and Consumption Report* for 1952–1953 had a value of $5,300 or greater (adjusted to 1993 dollars). Brown's report undoubtedly counts many lower-cost, nonreparable items that would not have been included in the D041 database of reparable parts. It is clear, however, that the value of aircraft spare parts has increased considerably in the intervening 40 years.

Air Force's motivation to have it serve as a test bed to expand and evaluate the potential of Lean Logistics. Finally, it presents an overview of the method of analysis used in this study.

THE PROMISE OF LEAN LOGISTICS—F-16 PRELIMINARY RESULTS

Initial investigations by RAND researchers into Lean Logistics focused on the F-16 fighter aircraft, in large part because of our extensive involvement in earlier logistics initiatives for that weapon system (see Abell and Shulman, 1992). A preliminary RAND analytic study of the F-16, undertaken in 1992, substantially reduced flow times for repair and transportation of aircraft spare parts and simplified the supporting logistics infrastructure. In that analysis, we assumed that commercial express carriers would be used for transportation of reparable assets and that parts would be repaired immediately upon being received, rather than being collected into batches for repair. Both of these assumptions were consistent with successful commercial practices. Consistent with commercial outcomes, these reductions in pipeline length—the time repair work was in process—led to improved responsiveness with smaller inventory requirements. Commercial experience suggests that additional savings, primarily from reduced need for support functions and personnel, should be possible as a result of procedural simplifications.

That pilot study found that reductions in pipeline length resulted in a more "robust" weapon system, one that was better able to react and respond to extreme variations in operating conditions and unexpected changes in tasking. An example of this uncertainty within the logistics system is disruption introduced by planning and procurement lead times. The inventory position (the amount and mix of parts in the system) must be established several years in advance of the availability of that inventory. At the time demands for those parts are registered (several years after planning), the amount and mix of parts then in the inventory may not correspond to the demand patterns being experienced by the Air Force.

To see how that situation might affect the F-16, we established the inventory available to the modeled F-16 fleet, using reparable-part demand and repair characteristics recorded in one year (1989), then

simulated performance of the fleet using demand and repair characteristics recorded in a later year (1992). This time lag is similar to the time lag experienced by the Air Force from procurement lead-time delays.

Under those conditions—using in 1992 the inventory that was "procured" in 1989—the current logistics infrastructure was able to support only 75 percent as many fully mission capable aircraft as would have been assumed in the planning year (that is, in 1989). By comparison, the high-velocity infrastructure being evaluated in that pilot study supported virtually the same number of fully mission capable aircraft under conditions seen in the later year (1992) as would have been assumed for it in the planning year (1989). In general, the high-velocity infrastructure was less sensitive to naturally occurring, but unpredictable, perturbations in the logistics system.

AN OPPORTUNITY FOR LEAN LOGISTICS—C-5 READINESS PROBLEMS

About the same time that RAND was initially investigating Lean Logistics concepts, Air Mobility Command (AMC) was encountering difficulties with the C-5 Galaxy aircraft. As the world situation changed, AMC found its airlift aircraft in increasing demand. Data from 1993 show, for example, that AMC's C-5 fleet was being tasked to fly well in excess of the 43,572 flight hours planned for that fiscal year. As of March of that year, the aircraft had already logged 34,217 flight hours, accumulating flying activity at a rate of 164 percent of the planning projection (AMC, 1993). The effect of this overflying was made worse by a shortage of stocks at overseas locations and by other technical problems—ultimately leading to a low readiness rating for the aircraft.[3]

Mission-capable rates for the C-5 have historically been low when compared with fighter and bomber aircraft. While AMC understands the reasons for the readiness rates generally achieved for the C-5, observers outside AMC often find these apparently low rates to be

[3]These problems may have been further compounded by the change at that time to the Weapon System Management Information System (WSMIS) for readiness reporting.

disturbing. A careful analytic study of the C-5 offered the opportunity both to assess the potential for Lean Logistics to improve C-5 performance and to understand more fully the causes of the apparently low C-5 logistics performance.[4]

C-5 GALAXY AIRLIFTER

Fielded in the early 1970s, the C-5 Galaxy is the Air Force's main heavy-lift logistics resource. With a fully loaded, unrefueled range of over 2,000 miles and the ability to carry more than 100 tons of cargo or 340 passengers, the C-5's versatility places it in demand for a wide range of missions. Some of the physical characteristics of this unique aircraft are shown in Table 1.1, contrasted with characteristics of several other USAF aircraft. The photograph of aircraft on display during an Air Force 50th anniversary celebration, shown in Figure 1.1, underscores the contrast in scale among various aircraft. A C-5 appears in the upper left corner of the photograph, with a C-17 to its right and a B-52 in the lower left. On the right side of the photograph, near the middle, we see a dart-shaped F-15, a cross-shaped A-10, and an F-16 at the extreme right.

C-5s are operated by the Air Mobility Command, Air National Guard (ANG) and Air Force Reserve (AFRES) components, and by the Air Education and Training Command (AETC). As of mid-1993, C-5 aircraft were assigned to these organizations as follows (see Table 1.2): 75 aircraft to AMC, 7 to AETC, and 44 to Guard and Reserve components. Using the estimated beddown developed for these analyses,[5] we find that 52 aircraft would typically be tasked with

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[4]See also Surrey et al. (1995) for a discussion of the Air Force's parallel assessments of Lean Logistics and the C-5 Galaxy.

[5]The term *beddown* refers to the placement of specific aircraft at specific locations and is more appropriate when talking about fighter aircraft than when talking about the C-5. Nonetheless, our modeling of C-5 operation required that we determine the number of aircraft generally operating out of each of the locations in our model—in essence, a beddown for C-5s. Table C.2 in Appendix C lists the beddown of aircraft used in the various cases of this study. Our use of a beddown for C-5s is strictly a modeling device; C-5s are not permanently located at particular bases, as fighter aircraft are.

Table 1.1

Physical Characteristics of Various Aircraft

Primary Function	B-52 Heavy Bomber	C-5 Outsized Cargo	F-16 Multi-Role Fighter	KC-135 Aerial Refueling
Number of Engines	8	4	1	4
Engine Thrust	17,000 lb ea.	41,000 lb ea.	27,000 lb	21,000 lb ea.
Wingspan	185' 0"	222' 10"	32' 8"	130' 10"
Length	159' 4"	247' 2"	49' 5"	136' 3"
Height at Tail	40' 8"	65' 2"	16' 0"	41' 8"
Max Takeoff Weight	48,000 lb	837,000 lb	37,500 lb	322,500 lb
Speed	650 mph	518 mph	1,5000 mph	530 mph
Range	8,800 nmi	6,320 nmi	2,000 nmi	1,500 nmi
Crew	5	7	1	4
Unit Cost	$30M	$184M	$20M	$52M
Date Operational	February 1955	June 1970	January 1979	August 1965

SOURCE: USAF.

Photo courtesy of U.S. Air Force

Figure 1.1—USAF Aircraft Parked on Display. The C-5 (upper left) is easily compared with bombers (left), other support aircraft (top row), and fighters (right side, middle). Note the cars parked along the left edge of the photograph (the small dots scattered across the field are people).

Table 1.2

Assignment of C-5 Aircraft

Unit	Base	Command	Number of Aircraft Authorized	Assigned	Possessed
436AW	Dover AFB, DE	AMC	35	38	32
60AW	Travis AFB, CA	AMC	35	37	32
105AG	Stewart Apt, NY	ANG	11	12	14
433AW	Kelly AFB, TX	AFRES	14	16	11
439AW	Westover ARB, MA	AFRES	14	16	11
97AMW	Altus AFB, OK	AETC	6	7	8
TOTAL			115	126	108

SOURCE: Private communication from HQ AMC, dated June 9, 1993.

NOTE: We have placed the number of aircraft shown as *possessed* at the various locations modeled, according to a procedure described in Appendix A. The remaining 18 aircraft (i.e., the difference between *assigned* and *possessed*) were assumed to be in depot-repair status. Note that, due to the effects of rounding and various assumptions that have been made in estimating the beddown, the inventory of aircraft used in this study is actually 109 rather than the 108 shown as *possessed* by the Air Force.

flying missions during peacetime and 57 would be untasked (an additional 18 would be in depot-maintenance status).

The C-5 fleet has substantial tasking, even in peacetime; significant numbers of C-5s are carrying out airlift missions at all times: It is in constant use—around the clock and around the globe. Although peacetime flying requires only about half the fleet, the peacetime flying rate for the C-5 may actually be greater than would typically be seen for fighter aircraft, judging from the flying hours accumulated per authorized aircraft.[6]

Because of its unique capabilities, the C-5 is often called on to support missions for which no airlift alternative exists. Supporting taskings that range from its primary mission of delivering combat equipment rapidly and in high volume, to missions delivering relief supplies to victims of man-made or natural disasters, the C-5 often ends up in locations that have minimal support capabilities and little

[6]As of March 1993, the C-5 fleet had accumulated slightly more than 2 hours per primary aircraft authorized (PAA) per day in that year. Typical projections for F-16 peacetime flying, by contrast, are on the order of 1 flying hour per PAA per day.

familiarity with this complex aircraft. The C-5 has a large number of reparable line items (given Air Force data, we modeled 1,625 unique reparable line items in this study)[7] that display a wide variety of performance characteristics.

C-5 Operations

The nature of the C-5's mission makes its operation unlike that of most other weapon systems. While most fighter and bomber aircraft are operated from fixed locations in relatively large numbers, the C-5 flies alone, along extended routes, usually to locations that will see a C-5 less than a dozen times a year.[8]

During 1992, C-5s made more than 18,000 landings at a total of over 400 locations, in every part of the world (summarized in Figure 1.2). Landing frequencies for individual locations ranged from over 3,000 per year at home bases, to only one per year at nearly one-quarter of en route locations—that is, locations away from home bases.[9]

Roughly one-third of all C-5 landings in 1992 took place at the CONUS main bases (Dover AFB, Delaware; Travis AFB, California; and Altus AFB, Oklahoma). Sixty-two percent of landings occurred en route. Four percent of landings occurred as part of support to then-ongoing operations in Somalia. The AMC-operated forward supply system (described in the next section) served 34 percent of landings; half of those were at AMC's forward supply locations (part of the FSS), and the other half were at remote locations supported indirectly by the FSS. Over one-quarter of all C-5 landings occurred at locations that are not in AMC's support structure at all. Only 5 percent of landings occurred at Guard or Reserve locations (about 1 percent of en route landings were of Guard or Reserve origin; we do not consider those landings separately in this study).

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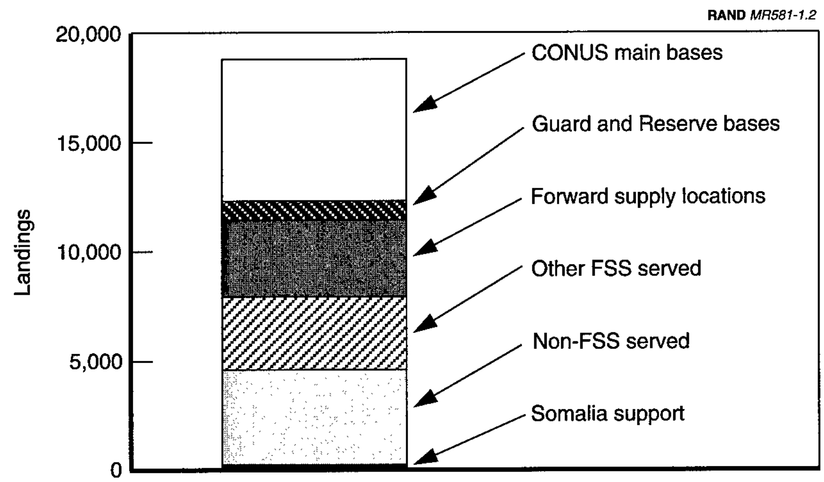
[7]Because of ambiguities in the data, these 1,625 unique NSNs (national stock numbers) appear as 1,908 parts.

[8]Other weapon systems sharing some of these characteristics include the C-141, C-17, KC-10, KC-135, and the E-3.

[9]AMC provided a database of landings for each location visited by a C-5 during 1992.



SOURCE: AMC database of landings for 1992.

Figure 1.2—Annual Landings by Type of Location. Over 60 percent of landings are away from home bases; over half of non–home base landings are served by AMC's forward supply system.

Extensive Logistics Support Structure

To serve its dispersed operations, AMC's logistics community has established a forward supply system (FSS). For the C-5, that system consists of two primary supply points (PSPs), Travis AFB and Dover AFB, which serve eleven forward supply locations (FSLs), and a handful of forward supply points. Each FSL serves landing sites within a specific geographic region. For the FSLs, the two PSPs function as both their supply depots and provider of repair services. The forward supply points provide a minimal AMC presence at a few forward locations and were being phased out at the time of this study.

Major maintenance of aircraft and retail (that is, AMC-controlled) repair of parts are conducted at the home bases (Dover AFB and Travis AFB for AMC). In general, no repair capability is available for C-5 parts en route. As C-5 aircraft conduct their missions, en route maintenance is conducted opportunistically by the onboard crew chief, by local personnel (when qualified), or by mobile repair teams

dispatched from AMC locations. Supply support while en route comes from the FSL serving the geographic region in which the need arises. For example, an aircraft landing at Aviano AB, Italy, and needing a replacement part will generally get that part from the FSL located at Ramstein AB, Germany.[10]

In addition to the FSS, AMC operates the Tanker Airlift Control Center (TACC), which exercises overall operational command and control for the entire air mobility system. The TACC provides an important backup to the FSS. It arranges for serviceable assets (and repair teams, when necessary) to be transported rapidly to grounded C-5 aircraft. When FSS supplies are either unavailable or are out of reach, or when specialized maintenance support is required, aircrews can call the TACC hotline to request support. The TACC will locate the needed part and identify the best available transportation (commercial or military) to get that part to the aircrew as quickly as possible.

The one-quarter of C-5 landings that occur at locations outside AMC's FSS are supported either directly by the PSPs; indirectly through lateral support from AMC, AETC, ANG, or AFRES locations; or directly by AFMC. While there was no direct evidence, AMC personnel expressed the belief that support practices at locations outside AMC's FSS were similar to those at locations in the FSS: A substantial proportion of maintenance (and, hence, supply) actions are deferred from en route locations to home bases.[11]

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[10]The transaction is actually accomplished as a lateral supply action—where one airbase donates a needed part to another airbase. Necessary paperwork follows to allocate the stock-fund charges to the correct account and to shift the supply demand from the Aviano AB Standard Base Supply System (SBSS) account to the SBSS account at Ramstein AB.

[11]We found some evidence that supply actions in support of activity at Western Hemisphere locations outside AMC's direct control are not visible to AMC. Demands recorded in the SBSS accounts monitored by AMC are not sufficient to explain demands that would be expected to arise from this activity. It seems likely that most of those demands are actually being supported by the wholesale system (that is, by AFMC) without AMC's knowledge. See Appendix A.

C-5 Is Substantially Different from Fighter and Bomber Aircraft

We had anticipated that much of our prior experience modeling and analyzing fighter and bomber aircraft would be directly applicable to study of the C-5. This, however, did not prove to be the case. The C-5 turns out to be different from fighter and bomber aircraft in several important ways. Some of the major differences we observed are indicated in Table 1.3, which contrasts the F-16 with the C-5.

Fighter aircraft, such as F-16s, are organized into squadrons of 18 or 24 aircraft. One or more squadrons typically operate out of a single location, with each squadron flying 20 to 30 sorties per day. By contrast, the C-5 lands at over 10 times as many locations as F-16s typically would. Although C-5 *main* bases may have 10 to 20 aircraft in residence, *most* bases have at most one aircraft present at any time. Activity levels, even at the main bases, are only a few sorties per day.

In modeling fighter aircraft, it is often sufficient to include fewer than a dozen bases in the analyses; most studies can be conducted with characteristic, or typical, bases. For the C-5, however, there are substantial differences among locations; studies of the C-5 should include all relevant bases individually.

Unlike fighters and bombers, C-5 supply and maintenance actions do not tend to occur at the same location. Maintenance actions occur wherever the aircraft happens to be; however, associated supply actions tend to occur at AMC-managed supply points. Separation of supply and maintenance actions tends to confound both analysis and management. To repeat the earlier example, when a maintenance action is taken on an aircraft currently located at Aviano AB, Italy, the supporting supply action will ultimately be recorded at Ramstein AB, Germany. In fact, when readiness spares package (RSP) assets are being used to support a location experiencing increased traffic, the nominal owner of the RSP assets (typically Dover AFB or Travis AFB) will be seen as the source of supply actions no matter where those actions actually occur.

Table 1.3

F-16 and C-5 Differences

Feature	F-16	C-5
Operating locations necessary to analyses	Less than 20	Hundreds?
Aircraft per base	12 to 72	1 to 23
Sorties per day	10 to 100	0 to 3
Sortie topology	Return to home	Stop en route
Supply & Maintenance	Collocated	Usually separate

Readiness rates for the C-5, as measured by mission-capable status—the degree to which aircraft can carry out their assigned missions—have never compared favorably with those for fighter aircraft. Whereas F-16 wings would typically expect well over 90 percent of their aircraft to be fully mission capable at any time, it is typical for less than 40 percent of C-5 aircraft to be listed as fully mission capable.[12] However, the design of the C-5 (as with most large aircraft) incorporates many redundant and backup subsystems, making it possible for the C-5 to fulfill many of its missions in a partially mission capable status (that is, with some subsystems not functional). Component failures in the course of a mission can often be ignored until the aircraft returns to its home base.

METHOD OF ANALYSIS

This study was conducted using the latest version (Version 6.4) of Dyna-METRIC (Dynamic Multi-Echelon Technique for Recoverable Item Control). Developed by RAND in the mid-1980s, Dyna-METRIC is an analytic tool for gaining an understanding of the implications of logistics-system alternatives for military capability and has seen wide application within the Air Force. Two versions of Dyna-METRIC are in common use: an older analytic version, which uses mathematical modeling (Isaacson, Boren, Tsai, and Pyles, 1988); and a more recent version, which uses Monte Carlo–based, discrete-event simulation (Isaacson and Boren, 1993). The later (simulation) version was used in this study.

[12]See Table C.3.

The model of C-5 operation and support that was developed under this study encompasses 20 bases, 6 intermediate support facilities, 1 depot complex, and 109 aircraft, each composed of 1,908 reparable line items (about 11,000 individual reparable assets on each aircraft). All simulations involved 10 trials of at least 360 days of operation.

Our model of C-5 operation and support was developed using data provided by AMC and AFMC. The usual approach to modeling demand rates and usage characteristics for parts is to apply worldwide average statistics maintained in data systems operated by AFMC for all parts at all locations. However, AMC was reluctant to rely on those "wholesale" data. AMC personnel explained that, in the past, they had found errors and anomalies in the wholesale data systems. Therefore, this study began by comparing wholesale data to data gathered by AMC through the Standard Base Supply System, a process that was complicated by AMC's lack of experience in gathering the type and volume of data needed. Air Mobility Command's expertise with these data rapidly improved as the study progressed. In the end, parts data for our models were generated from AFMC's wholesale data and combined with comparable data gathered by AMC.

A substantial amount of C-5 maintenance and supply activity is deferred to home bases while C-5 aircraft are en route. Wholesale data alone do not adequately represent the demands experienced for the C-5. To address this problem, we developed two sets of part-demand rates: one to represent supply activity away from home bases and one to represent supply activity at home bases.

The operating tempo and locations of aircraft used in our models were derived from AMC data on the locations at which C-5s had landed in 1992 and the number of landings that occurred at each site. Model inputs had to be derived, because AMC did not have estimates of the average number of aircraft operating in each of its logistics service regions and their activity rates while on missions. Although our derived beddown of aircraft was reviewed by AMC, it remains unclear how well our assumptions match actual AMC operating experience.

As the model was developed, model inputs and simulated performance results were reviewed by AMC. The model and its inputs were

revised and re-evaluated until a satisfactory approximation of Air Force experience was achieved. That model then served as the basis for further analysis and is referred to as the "standard infrastructure" throughout this report.

We developed an alternative infrastructure—referred to as the "high-velocity infrastructure" throughout this report—by shortening elements of the logistics pipeline in the standard infrastructure. For this model, we assumed the use of commercial express carriers and industrial management practices similar to those in the commercial sector.

Inventory levels for each infrastructure were established on the basis of the rules found in AMC Supplement 8 to the *USAF Supply Manual,* AFM 67-1, Volume II, Part Two, Chapter 19 (April 27, 1992b; now AFMAN 23-110). Under those rules, the amount of inventory assigned to each location is a function of the pipeline length (the time it takes to replace a broken part with one ready for use), historical demand rates, the planned future operating tempo, and the amount of stock set aside to protect against variation in demand rates.

The peacetime beddown of aircraft and the flying program were estimated by a RAND-developed model, using AMC data for C-5 landings in 1992.

Performance of the standard and high-velocity infrastructures was compared under operating conditions that match those used in computing inventory levels. Excursions from that baseline scenario involved making adjustments to various key parameters exogenous to the logistics system, such as demand rates and variability, operating tempo, and availability of commercial transportation. Other excursions involved varying assumptions about the logistics system itself, such as the use of management adaptations, the distribution of aircraft in the system, and the presence and number of PSPs.

Accounting for the mission-capable status of aircraft posed a particular challenge in this study. The mission-capable status of aircraft is a primary analytic metric for both the Air Force logistics system and for these analyses. We touch on the comparison of our outcome measures to AMC performance reports in Chapter Two. Here, we note that the definition of *mission-capable status* for the C-5 has been somewhat problematic from the outset.

For example, it may be that the status of an aircraft en route is established only at AMC-manned locations; at other locations, the most recently reported status (probably better condition) may be assumed. This discrepancy makes interpretation of AMC mission-capable statistics difficult. In addition, the considerable redundancy in the design of the aircraft and the presence of a maintenance crew chief on board contribute to the resilience of the aircraft but further cloud the measurement of mission-capable status.

This study focuses almost entirely on peacetime flying, most of which is done by AMC and AETC aircraft. However, we included Guard- and Reserve-component aircraft in this study for several reasons:

- Guard and Reserve stocks have an effect on the overall system, primarily through lateral-supply actions as directed by the TACC.
- Fleetwide performance measures are affected by Guard and Reserve aircraft.
- Guard and Reserve aircraft are used in the major-operation scenario discussed in Chapter Three.

REPORT ORGANIZATION

In this chapter, we have reviewed the background of Lean Logistics and the current study, and have briefly described the C-5 Galaxy aircraft and its operation and support.

Our initial efforts under this study were devoted to achieving a baseline simulation that produced results comparable to the performance experienced by AMC. Chapter Two compares our baseline simulation results for the standard infrastructure with data reported by AMC. It then compares those simulation results with simulated performance of the high-velocity infrastructure.

One expectation of a high-velocity infrastructure is that it will adapt more quickly to change. In Chapter Three, we show results for four excursions from the baseline scenario, each of which places an extra burden on the system and each of which results in decreased performance.

In Chapter Four, we consider the sensitivity of our results to some of the assumptions underlying the logistics systems being compared, as well as what would happen if transportation were disrupted or if inventory reductions were implemented before process improvements could be put in place. We also consider the effectiveness of priority distribution and the presence of inventory at forward supply locations.

In Chapter Five, we summarize our conclusions from the research. The report closes with three appendices containing more-detailed data. Appendix A outlines the structure of these analyses and illustrates the approximations we have made in the process of modeling the C-5. Appendix B discusses excursions made in the course of this research in an attempt to understand why and how performance of the C-5 is limited. While not formally tied to the notion of a high-velocity infrastructure, those observations may prove useful in understanding how to extend the results of this study. Tables of results from some key cases considered in this study are found in Appendix C. At the end of the front matter, we include complete definitions of the many technical terms used in the analysis.

Chapter Two

RESULTS FOR A BASELINE SCENARIO

A high-velocity infrastructure (HVI) would reduce flow times for reparable components throughout the logistics pipeline. In this analysis, we have assumed a fairly aggressive level of innovation to produce a high-velocity infrastructure that, nonetheless, appears to be feasible:

- next-day delivery of *all* depot-level reparables within CONUS (both forward and retrograde)
- delivery of reparables to all locations overseas in two days
- wholesale repair-flow times that are approximately the same as the hands-on repair time for each part.

Commercial express carriers routinely accomplish next-day delivery of goods within CONUS. Two-day delivery to overseas locations is possible for most major locations.[1] Difficulties with customs in some countries remain to be resolved and are being actively worked out in both the commercial and government sectors.

Repair-flow times at the retail (base) level often approximate hands-on time, largely because efficient utilization of repair resources is not a primary consideration at that level. Existing management expectations at the wholesale (depot) level emphasize efficient utilization of repair and manpower resources—that is, utilization very close to

[1]More-recent (1998) experience with commercial express service to remote overseas locations suggests that 2-day service may still be optimistic. For example, service to Doha, Qatar, in 1998 averaged over 10 days.

their capacity limits. As a result, the wholesale repair system routinely repairs parts in batches—a practice that causes repair-flow times (the time from receipt of a part at the depot to its being available for issue as a serviceable) to be substantially longer than the actual repair effort. Although a major change in the way repair activities are managed at the wholesale level would be required, experience at the retail level suggests that such a change would be technically feasible. For the high-velocity infrastructure, we assume that depot-level repair-flow times can be reduced to very nearly the hands-on repair time for each part.

Throughout this study, we assume that repair resources are unconstrained—that is, that repair resources (test and repair equipment, consumable parts, and technicians) are adequate to complete repairs in the times indicated, both at the depots and at the air bases. The current and assumed pipeline flow times used in this study are summarized in Table 2.1.[2]

Table 2.1

Summary of Pipeline Segment Flow Times

	Flow Times for Respective Infrastructure	
Pipeline Segment	Current (days)	High Velocity (days)
Retrograde to PSP	8	2
Retail repair	2 to 7	2
Lateral support (i.e., TACC action)	2	2
Retrograde to depot	17	Next day
Depot repair	54, average	7, average
Forward from depot	17	Next day
Forward from PSP	4	2

NOTE: *Retrograde* is movement rearward, from an air base, to or toward the depot. *Lateral* is movement from one air base to another. *Forward* is movement from a rearward location (e.g., depot) to or toward an air base.

[2]The "Current" times shown in the table and used in this study are drawn from Air Force standard databases and reports for 1992–1993. The "High Velocity" times shown are posited by us on the basis of our understanding of applicable commercial practice. As discussed in Appendix A, data from an Air Force (AF/LMC) review of logistics support to the C-5 during Desert Storm suggest that the "Current" times listed may, in fact, be somewhat optimistic (Crimiel, 1991). See Appendix A for a more detailed discussion of the times we used.

In this chapter, we compare our model of C-5 operation under the standard infrastructure with AMC experience, then compare those simulated results with results achieved when a high-velocity infrastructure is assumed.[3] An AMC performance report from the month of March 1993, reflecting 12 months of performance data, was used as a benchmark for our modeling effort and is summarized in Table C.3 (AMC, 1993). The model produced an estimate of performance that is similar to AMC's actual experience, but that tends to underestimate it. When the hypothesized high-velocity infrastructure is compared with the standard infrastructure, we find that it would provide comparable or slightly improved performance of C-5 aircraft.

SIMULATION APPROXIMATES AMC EXPERIENCE

Our first task was to develop a model of C-5 operations and logistics that produced results representative of Air Force experience. Personnel at AMC were initially skeptical of this effort: They reported that earlier Air Force attempts to model the C-5 and its logistics infrastructure had produced results that did not match their experience. It was important, therefore, that the model we developed reflect AMC experience, and that we be able to explain to AMC personnel those differences that did appear. See Appendix A for a description of our model.

The two primary performance measures used in this study are mission-capable status and departure reliability. These measures in our results mirror and approximate measures used by AMC, enhancing our ability to validate our model using AMC historical performance data. Another measure used by AMC—issue effectiveness—had to be rejected for comparison purposes because it proved to be a poor means of comparing the standard infrastructure with the high-velocity infrastructure (see the section "Issue Effectiveness Declines" later in this chapter).

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[3]See Appendix A for a discussion of the way we modeled the C-5 and conducted the analyses in this study.

Mission-Capable Status

Mission-capable status reflects the proportion of aircraft that can fly all, at least some, or none of their assigned missions. Mission-capable status is usually reported in five categories. The highest category, *fully mission capable* (FMC), indicates that the aircraft can fly *all* of its assigned missions. In general, this means that all subsystems on the aircraft are fully functional. At the other end of the spectrum, categories for *not mission capable* (NMC) indicate that an aircraft is unable to fly *any* of its assigned missions because one or more critical subsystems are not available. Between these extremes are categories for *partially mission capable* (PMC), which indicate that an aircraft can fly some, but not all, of its assigned missions. Both the PMC and NMC categories are further subdivided to indicate whether the condition is due to a shortage of maintenance resources, *M* (PMCM or NMCM) or due to a shortage of supply resources, *S* (PMCS or NMCS).

Dyna-METRIC does not measure delays caused by maintenance shortages and therefore does not report aircraft in the PMCM and NMCM categories. These are conditions that generally arise when a shortage of resources other than parts prevents work from being done on the aircraft itself (for example, when no maintenance technician or crew chief is available to do the work).[4] Aircraft that would, in reality, be PMCM or NMCM are reported by Dyna-METRIC as if they were FMC. Throughout the remainder of this report, we use the symbol "FMC+" to refer to simulation results that report the aggregate of FMC, PMCM, and NMCM aircraft.[5]

A more subtle challenge is posed by the PMCS category. For an aircraft to be considered partially mission capable, it must be able to undertake some, but not all, of its assigned missions. We may think of the subsystems on that aircraft as divided into two categories: those that are essential to the operation of the aircraft and those that are not essential to the operation of the aircraft. Parts in the former

[4]This shortcoming affects only the comparison of mission-capable rates reported by the simulation with those reported by AMC. It has no effect on other results or conclusions in this study.

[5]Since the changes being considered in this study at the base level are in the supply system, the FMC+ measure is entirely appropriate.

category are sometimes identified on a minimum essential subsystem list (MESL). Although there was such a list for the C-5, AMC personnel informed us that they believed it to be unreliable; we were not able to make use of it.

We were able to use AMC-provided demand data to generate such a list of our own. By comparing worldwide average demand rates (as recorded in the Air Force standard D041 data system) with demands reported at each individual base (through the SBSS), we identified 87 unique parts that were demanded at the same rate, relative to operational activity level, throughout the world.[6] These parts may be reasonably thought of as "essential" in that we found no evidence that supply actions involving them were being deferred from overseas locations to home bases. We used this list of parts to get an estimate of the PMCS rate our model would predict.

Figure 2.1 reflects mission-capable rates experienced in the active portion of the C-5 fleet (that is, AMC and AETC aircraft; reports for Guard and Reserve aircraft were not available). The chart shows the average of 12 monthly reports dating from April 1992 through March 1993.[7] Those rates are compared with the corresponding rates observed in our simulation.

The simulated rate for FMC+ is 58 percent, which falls just below the range of values reported by AMC (62–71 percent) and below the reported average of 66 percent. The simulated PMCS rate of 13 percent understates the average of reported values (19 percent) and falls below the range of reported values (15–24 percent). The resulting 29 percent NMCS rate from the simulation overstates the average of reported values (14 percent) and falls above the range of reported values (12–16 percent).

Our model makes use of only the peacetime operating stock (POS) available to operating units. In practice, AMC logisticians also have available to them assets contained in the readiness spares package (RSP; that is, war reserve materiel). This larger pool of assets can

[6]See Table C.11 for a list of the parts chosen. While useful for our purposes, this list should not be viewed as definitive and is likely to change over time. However, we believe our procedure may have some utility beyond this study.

[7]See also Table C.3.

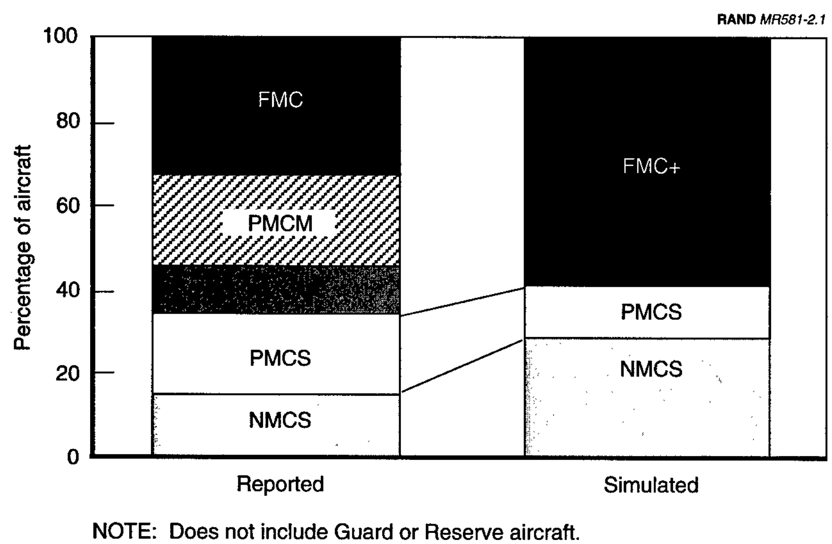


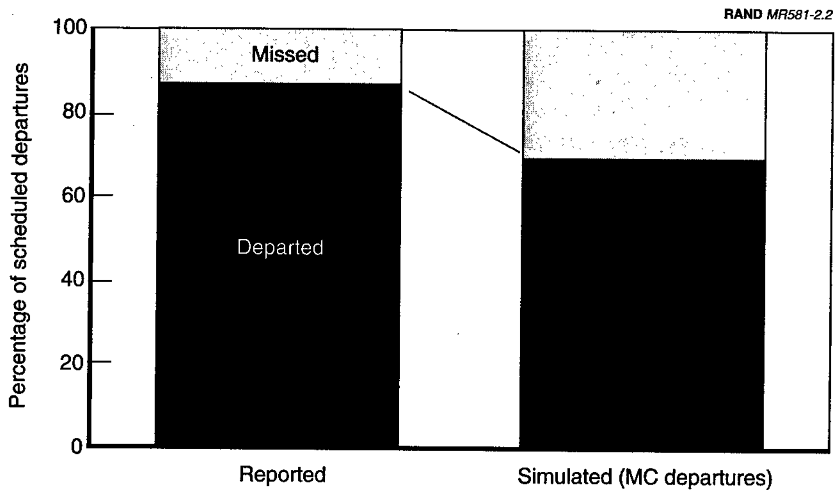
Figure 2.1—Reported and Simulated Mission-Capable Rates. Simulated mission-capable rates approximate those reported by AMC.

serve as a buffer against unexpected events, improving measured performance—a buffer our simulations did not take advantage of.

Departure Reliability

Departure reliability represents the proportion of sorties flown on the day they were scheduled. Air Mobility Command reports departure reliability for Travis AFB and its served en route locations, and for Dover AFB and its served en route locations. We present those rates in Figure 2.2, along with the comparable measures taken from our simulation. The indicated 69-percent successful departure rate understates AMC's average over 12 monthly reports (April 1992–March 1993) of 87 percent, and falls below the reported range of 82 to 92 percent.

This understatement may arise, in part, because scheduled sorties that are known to be unflyable ahead of time (for example, the day before) are often rescheduled by AMC and are not counted as



NOTE: Does not include Guard or Reserve aircraft.

Figure 2.2—Reported and Simulated Departure Reliability. Simulated departure reliability understates AMC experience.

"missed" sorties. Such sorties are always counted as "missed" in the simulation. This problem is confounded by uncertainty about what C-5 pilots will accept as the flying condition of their aircraft (in the figure, we show the simulated result for FMC+ and PMCS departures combined, called the mission-capable—or MC—departures).

As described in Chapter One, the C-5 is a very robust system, having both backup subsystems and its own onboard maintenance capability. The presence of an onboard crew chief influences the observed departure reliability for the aircraft because minor repairs and adjustments can be made en route. The opportunistic nature of these actions makes them extremely difficult to account for in the model.[8]

[8]Note also that, because the model "flies" only FMC sorties, we do not simulate the same flying program as executed by AMC. Since the model completes only around 70 percent of the scheduled sorties, a smaller number of aggregate demands for parts is being generated and may be reflected in a slightly higher parts availability than is appropriate.

COMPARABLY STOCKED HIGH-VELOCITY INFRASTRUCTURE PERFORMS SLIGHTLY BETTER

To make the baseline and all subsequent comparisons, we began by providing each infrastructure with equivalent inventory. By *equivalent* we mean that the same computations were used for all cases. The rules for those computations were taken from AMC Supplement 8 to AFM 67-1[9] and are implemented in the Standard Base Supply System (USAF, 1992b). The amount of inventory computed in this way depends mainly on the length of the logistics pipeline—the amount of time it takes the logistics system to turn a broken part back into a usable one. Since the lengths of the pipelines supported by the standard and high-velocity infrastructures being studied here are vastly different, it should come as no surprise that the two infrastructures end up having substantially different amounts of inventory in them (see the section "Inventory Requirement Is Reduced" later in this chapter).[10]

As Figure 2.3 indicates, performance of a comparably stocked high-velocity infrastructure is slightly better than that of the standard infrastructure in that it has more FMC+ aircraft and fewer NMCS aircraft. Here, the performance indicated is that of the entire fleet, as distinct from Figures 2.1 and 2.2, in which only the active portion of the fleet was examined. Similar performance results are not surprising: The SBSS allocation algorithm, which is designed to achieve a fixed level of issue effectiveness under planned-for condi-

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[9]Air Force formal documentation has since been reissued under a different numbering scheme. The relevant rules are now found in AFMAN 23-110, which retains the same Volume, Part, Chapter, and Supplement numbering as AFM 67-1.

[10]Our calculations produce inventory "levels" (sometimes called the *requirement*) for each location. The simulation begins by assuming that these levels are fully funded; that is, it assumes that there are assets corresponding to each level at each location. As the simulation is run, the assets in the system get redistributed according to the operating rules being modeled. In general, assets have been redistributed from the wholesale (depot) to the various retail (base) locations on the basis of the performance improvement that was expected to result (called "priority distribution" in Dyna-METRIC). In addition, we have allowed lateral movement of assets (from one base to another) when such movement would bring an aircraft up (i.e., make it operational).

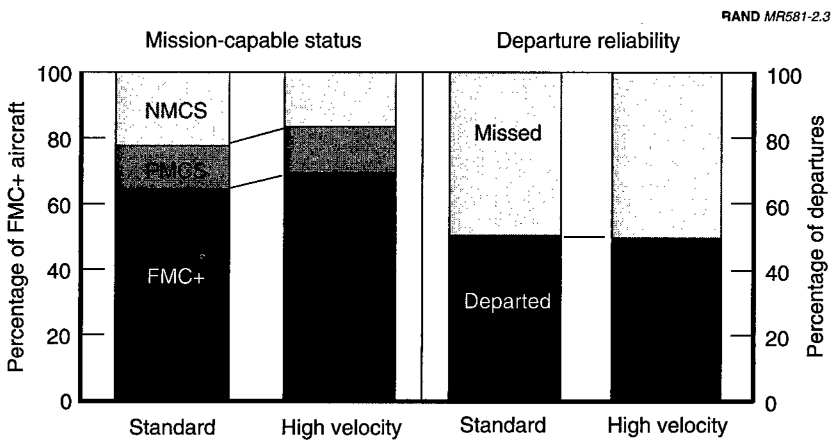

Figure 2.3—Baseline Performance Under Standard and High-Velocity Infrastructures. The high-velocity infrastructure produces slightly more mission-capable aircraft and departures.

tions, is working as expected.[11] Details of these and other results are given in Appendix C.

The following extract from Table C.7 indicates that performance at the major CONUS bases tends to be quite good (roughly 83 and 80 percent FMC+ for active-CONUS and Guard-and-Reserve bases, respectively, under the HVI), owing mainly to the relatively large numbers of aircraft at those bases. There is little room for improvement in the performance at those locations. Performance at the FSLs and other en route bases tends to be substantially lower than at the main bases (under the standard infrastructure, the simulation finds roughly 12 percent of aircraft at en route locations to be in FMC+

Case	Infrastructure	CONUS Main	Guard & Reserve	En Route	Fleetwide
Baseline	Standard	82.3%	79.7%	11.7%	65.9%
	High Velocity	83.8%	86.2%	12.5%	68.9%

[11]*Issue effectiveness* is a measure of the likelihood a technician will get an asset from the supply system at the time the request for that asset is made.

status). We surmise that this situation is due largely to the small scale of operations at en route locations, a situation that is inherent to the C-5's mission.

The results presented in Figure 2.3 were produced by a Monte Carlo–based discrete-event simulation, and are averaged over 10 independent trials. In Figure 2.4, we present the number of FMC+ aircraft observed under the standard and high-velocity infrastructures for each of the 10 trials. Performance under the HVI is routinely better than that under the standard infrastructure. While there is variation in simulated performance from trial to trial, the observed effect appears to be quite consistent.[12]

The inventory calculations used by the Air Force and emulated in this study are intended to produce similar performance under the two infrastructures, assuming that planning factors are realized in execution. However, commercial practice and our pilot study lead us to believe that an HVI would perform slightly better than the standard infrastructure whenever the system is under stress. For example, whenever the number of demands experienced at a particular location exceeds the number estimated by the allocation algorithm, the HVI should be able to replenish the needy location faster than the standard infrastructure could. In general, performance should be slightly better.

To identify the relative advantages of an HVI under those stressful conditions, Chapter Three explores a number of scenarios that place the system under stress. The baseline scenario previews those results: Once in a while, even under the baseline scenario, demands

[12]A technical note of caution is appropriate in conjunction with these and all later side-by-side comparisons of the standard and high-velocity infrastructures. As with all discrete-event simulations, it is necessary to run these simulations for a long enough time in each case to allow the simulated system to come to steady-state operation. Detailed review of simulation results leads us to speculate that, while the high-velocity infrastructure cases come to steady-state operation prior to the end of the simulated year used in this study, the standard infrastructure cases may not have achieved steady state at the end of that simulated year (i.e., their performance is still falling). If that is the case, the comparisons shown throughout this report systematically *understate* the difference between the standard and high-velocity infrastructures; thus conservatively stating the benefits of an HVI.

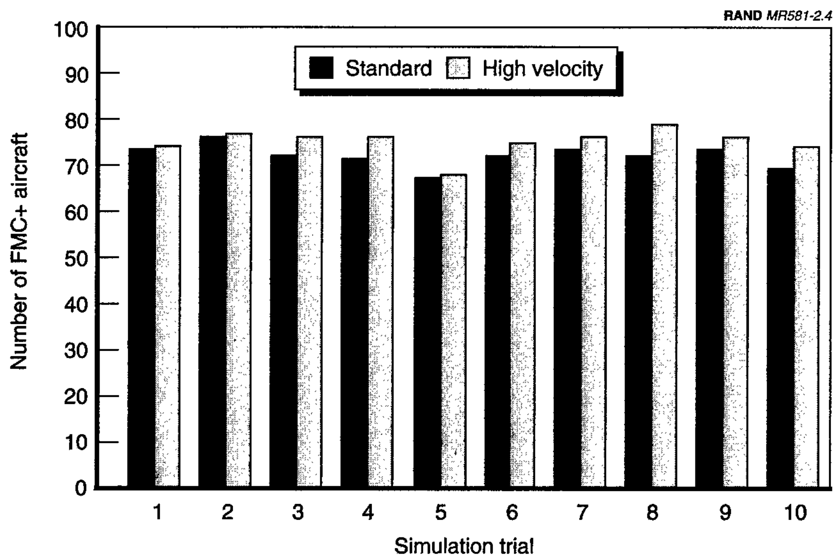

Figure 2.4—Trial-by-Trial Comparison of Simulation Results. The simulated number of FMC aircraft under the HVI (gray bars) is routinely slightly better than that under the standard infrastructure (dark bars).

on supply will exceed the allowances made at some location. Logisticians can take a limited number of actions (sometimes referred to as *management adaptations*) to correct such circumstances. For example, they can remove a needed part from one aircraft to install it in another (*cannibalization*), or they can appeal to nearby locations to provide a needed part (*lateral support*). Where those management adaptations are not available, and when stock allowances are small to begin with, the effects of an HVI should be most apparent. The en route locations, with just such conditions, provide a test.

Figure 2.5 compares mission-capable status under the standard and high-velocity infrastructures, as seen at the en route locations. The HVI produces 1 percentage point more FMC+ aircraft and 14 percentage points more PMCS aircraft than does the standard infrastructure.

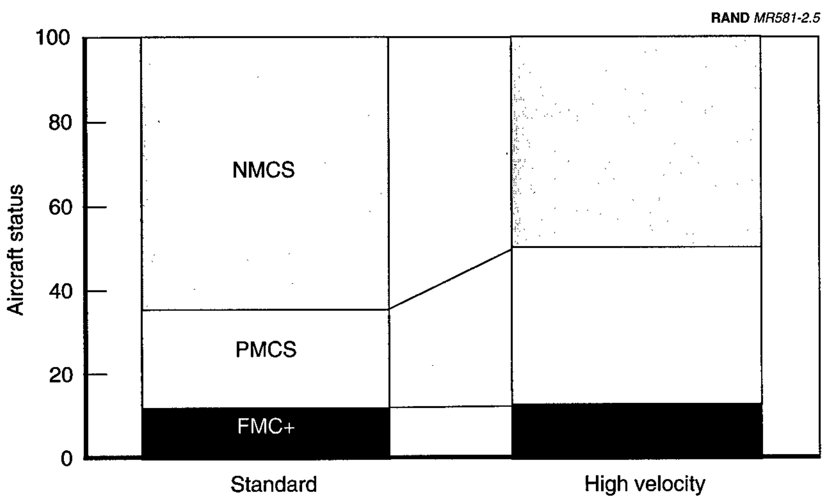

Figure 2.5—Baseline Performance at En Route Locations. A high-velocity infrastructure would produce slightly better performance en route under baseline conditions.

CANNIBALIZATION MASKS HVI EFFECTS AT MAIN BASES

We might have expected an HVI to have a greater effect on *overall* system performance, given the difference in capabilities of the standard and high-velocity infrastructures: Every time the system finds itself out of stock on some item, it takes the standard infrastructure more than eight times as long (on average) to produce a part as it takes the high-velocity infrastructure (i.e., 67 days full round trip versus 8 days, including the possibility of repairing the item within the relatively faster retail system). That difference is evident when we look at the en route locations, as in Figure 2.5. But why don't we see it at CONUS bases?

The answer lies in the principal management adaptation available at the CONUS bases but not available at en route locations—cannibalization. Of the aircraft at AMC main bases, more than half are untasked at any time. For Guard and Reserve bases, that ratio is closer to 11 to 1. So, at CONUS locations there are generally large numbers

of aircraft without flying commitments from which parts can be cannibalized.

Even though cannibalization represents a small proportion of maintenance actions (in 1992, AMC reported cannibalization rates of 2–5 actions per aircraft per month, out of 1–3 total maintenance actions per aircraft *per day*), those actions can be extremely valuable.[13] Their general effect is to increase the apparent amount of inventory (one element of what is sometimes referred to as the "logistics mass") at CONUS locations. Cannibalization of parts is used as a safety net, protecting the base against unexpected swings in demands.

The effect of cannibalization on performance at CONUS bases is illustrated in Figure 2.6. The chart shows mission-capable status (percent of FMC+ aircraft) and departure reliability, averaged over the six main CONUS bases. It compares the outcome when cannibalization is aggressively pursued ("Full cannibalization") and when it is disallowed ("No cannibalization"). The effect is exaggerated in this display because of the way cannibalization is modeled in Dyna-METRIC.[14] While the absolute effect of cannibalization is overstated in the figure, comparison of the effect under the standard and high-velocity infrastructures is instructive.

As shown in Figure 2.7, the simulation finds that, if cannibalization at CONUS bases were not allowed, mission-capable status at those bases would be comparable to mission-capable status at en route locations, where cannibalization is not possible. Performance at CONUS bases is still slightly better because of the proximity of the supply points associated with CONUS bases, each of which is

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[13]In reviewing a draft of this report, AMC personnel noted that cannibalization rates had increased, to 5–10 cannibalization actions per aircraft per month from July 1994 through June 1995. They point out that cannibalization (when feasible and appropriate) can produce a needed part *and all associated hardware,* whereas getting the part through supply can result in the technician having to return the next day to requisition associated hardware.

[14]On the one hand, when cannibalization is allowed, Dyna-METRIC uses it more often than it would be used in practice. On the other hand, without cannibalization, Dyna-METRIC tends to overstate the number of grounded aircraft when the flying program is small relative to the number of aircraft available (as is the case for CONUS bases).

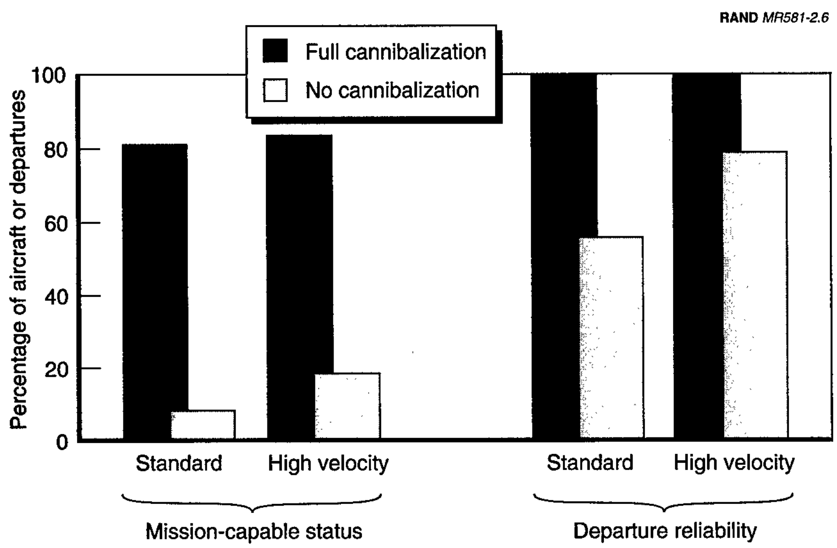

Figure 2.6—CONUS Performance With and Without Cannibalization. The use of cannibalization masks the effect of HVI at CONUS bases.

modeled as being half a day away from its backshop, where relatively large amounts of stock are housed.

An effect for the high-velocity infrastructure *is* observed in these results. Without cannibalization, mission-capable status would be over 11 percentage points better at CONUS bases under an HVI than under the standard infrastructure. Departure reliability at CONUS bases under an HVI would be roughly 22 percentage points better than under the standard infrastructure if cannibalization were not allowed in either case.

One conclusion is that we should expect fewer cannibalization actions to be required under an HVI at CONUS main bases, but that those cannibalization actions that do occur should generally be more valuable (i.e., more effective).[15]

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[15]We are not advocating restrictions to cannibalization. Cannibalization is, and will remain, an important management adaptation that, when used wisely, can significantly improve readiness.

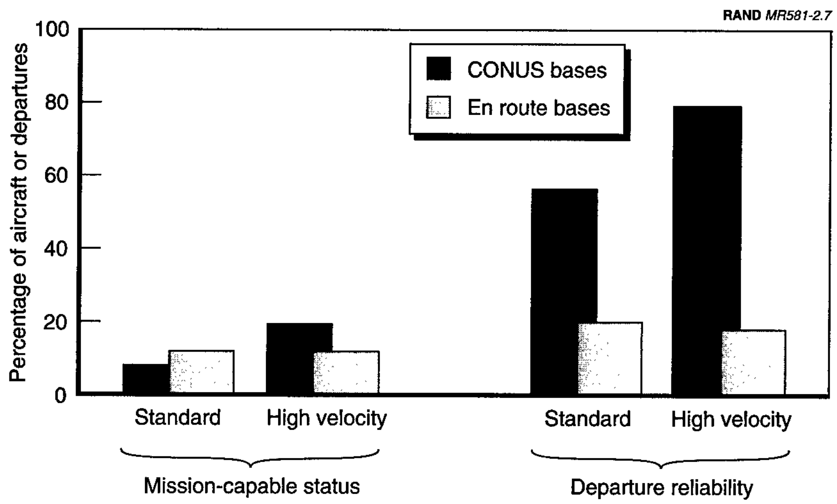

Figure 2.7—CONUS Performance Without Cannibalization Compared With En Route Performance. Disallowing cannibalization at CONUS bases would reduce mission-capable status levels to those at en route bases; departure reliability would be affected less severely.

ISSUE EFFECTIVENESS DECLINES

Another performance measure we considered in this study was *issue effectiveness*—a measure of the supply system's ability to provide a needed part at the time a request is made. It may be interpreted as the proportion of times someone arriving at a supply outlet found the part they were looking for at that outlet, at that time. Issue effectiveness is a widely used measure of supply system performance and, as such, was originally expected to be important in this study. However, as the study progressed, we were reminded that the high-velocity infrastructure, by its very nature, uses speed of processing to produce operational performance whereas the standard infrastructure uses mass of inventory. As a result, the high-velocity infrastructure tends to have lower issue effectiveness at bases than the standard infrastructure, even though both infrastructures are supporting the same operational performance.

Figure 2.8 charts issue effectiveness reported by AMC (leftmost bar) with simulation results for both the standard infrastructure (middle bars) and the high-velocity infrastructure (right bars) for the baseline case. The bars on the chart represent the range of effectiveness values reported or found. The value at the top of each bar is the highest effectiveness reported; the value of the bottom is the lowest. AMC reports a single issue-effectiveness measure monthly.[16] Over the course of a year (April 1992–March 1993), it reported that between 73 and 80 percent of requests were filled at the time the request was made.

In our simulation, we are not able to observe supply issues when they occur. However, we can observe the number of requests on supply that could have been filled on the same day (1) before any new stocks

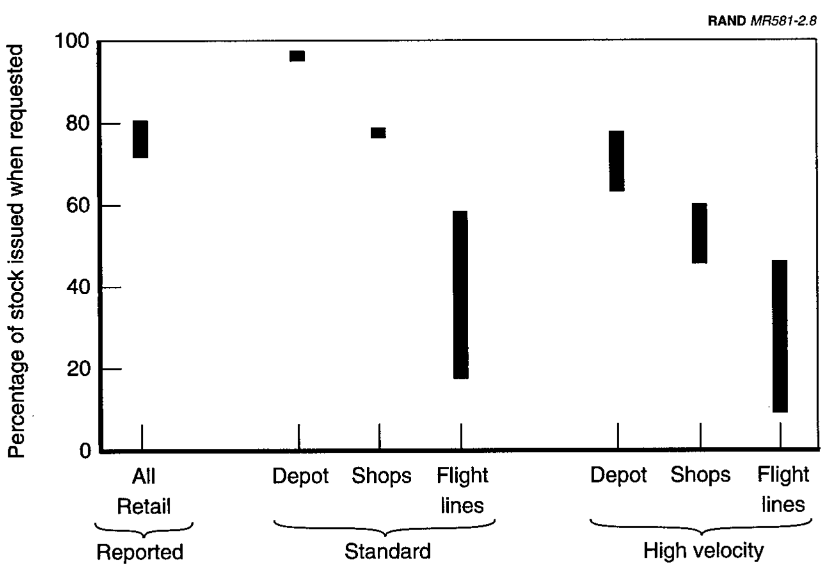

Figure 2.8—Baseline Comparison of Issue Effectiveness. A decline in issue effectiveness does not result in reduced performance.

[16]We believe, but were not able to confirm, that AMC's issue-effectiveness data include all items issued through retail supply, not just the reparable items included in

arrived (or repairs were completed) and (2) after all new stocks had arrived (and repairs were completed). These conditions define a window characterizing issue effectiveness; actual effectiveness would fall somewhere in that window. We observe the separate issue effectiveness at each echelon: at the depot, at CONUS main-base backshops, and at the flight lines.[17]

In Figure 2.8, we see, not surprisingly, that issue effectiveness under the standard infrastructure is generally better than that under the high-velocity infrastructure. By relying on speed of processing and delivery rather than on inventory, the HVI is able to sustain the same performance levels as the standard infrastructure with a lower issue-effectiveness rate.[18]

While not a technical concern—the same operational performance is being achieved in each case—lower issue effectiveness under an HVI is likely to raise some institutional concerns. To the extent that a crew chief would get a needed part *on demand* less often, some dissatisfaction with the HVI should be anticipated at that level. However, when the system is viewed as a whole, reduced issue effectiveness is not an impediment to performance and should be viewed as acceptable.

In the end, the Air Force will have to establish either a new definition for issue effectiveness (tailored to the HVI) or new performance

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our simulations. In that case, AMC's figures probably overstate its experience with reparable parts.

[17]Note that depot-related measures are suspect, because our allocation of assets to the depot does not mimic any of the processes used by AFMC for that purpose.

[18]Reviewer Chris Hanks has pointed out that another way of expressing the relationship between issue effectiveness and the speed of the logistics system is through the equation

$$EBO = d \times (1 - r) \times w$$

where *EBO* is the expected number of backorders for a part, d is the demand rate for the part, r is the rate at which demands are immediately satisfied, and w is the average wait for unsatisfied demands to be satisfied. Hence, as the logistics pipeline is shortened (w is reduced), the same performance (*EBO*) can be achieved with a lower issue effectiveness (smaller r). This expression is an example of Little's formula from queueing theory, which captures the intuitively appealing idea that the average number of items in a process is given by the rate at which items arrive at the process *times* the duration of the process.

standards for issue effectiveness that reflect the realities of high-velocity infrastructures.

INVENTORY REQUIREMENT IS REDUCED

An HVI would enable the C-5 fleet to achieve substantially the same performance *with roughly one-sixth the inventory requirement* of the current infrastructure, and that reduced inventory would cost one-third what it would cost to meet the requirement for the current inventory (see Figure 2.9).[19]

Since the Air Force already owns most of this inventory, few inventory dollars would be saved *immediately* from implementation of HVI. Such savings would have to be accrued over time, as a result of

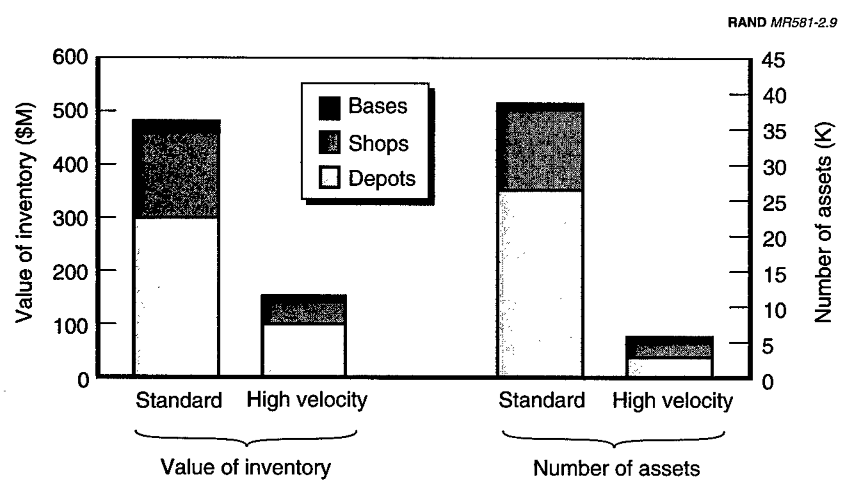

Figure 2.9—Pipeline Inventory Requirements Under Standard and High-Velocity Infrastructures. Substantially less inventory is required under the high-velocity infrastructure to achieve the same performance.

[19]Note that this figure represents only what is called the "pipeline" requirement. Other sources of requirement include Foreign Military Sales, use of these parts on

reductions in both the inventory requirement for new systems and outlays made to adjust current inventory. The former savings would occur whenever a new system entered service under an HVI, since it would have a smaller initial-provisioning inventory requirement.

The latter savings would come about because inventory levels, even for mature systems, are constantly being revised and adjusted. In a study of component reliability for F-16 aircraft, Abell et al. (1988) called this constant adjustment to inventory levels *churn.* Churn in inventory levels results from the introduction of new parts, replacement of old parts with improved versions, evolving experience with existing parts, and the upgrading of weapon systems. For the F-16, Abell et al. (1988, p. vi) found that shifting part characteristics (demand rate, repair time, reliability, etc.) "can induce the need for annual expenditures on spare parts equal to 16 to 21 percent of the total cost of all the spares in the system."

Given the current fiscal environment, the rate of modification and upgrading may be slowed substantially from that of the late 1980s when the F-16 study was conducted. Assuming that the effects of churn were restricted to only 10 percent, we might expect to see as much as $32 million in annual savings from reduced inventory requirements.[20] Actual savings, of course, would be a function of how and when changes in the infrastructure were implemented, and how currently owned inventory influenced future investment decisions.

other weapon systems, and programmed depot maintenance, all of which may contribute to the total inventory requirements.

[20]Any such savings would be partially diminished by increased costs from the use of express transportation. To get a feel for how much additional transportation cost might be expected, we can look at the traffic in reparables generated by our simulations. On average, the simulation reported 218 daily wholesale moves (both *carcasses* [broken parts] and *serviceables* [fixed parts]), for a total weight of about 7,700 pounds. There were about 100 daily retail moves (between bases and the PSPs), for a total weight of about 5,700 pounds moved. Assuming a rate (in 1992) of about $1 per pound for the current infrastructure (approximately U.S. Postal Service package rates) and about $2 per pound for a high-velocity infrastructure (roughly Federal Express next-day rates), the high-velocity infrastructure might incur an additional $4.9 million annually. While very rough, these calculations suggest that the increased costs for transportation should be insignificant compared with the savings available from inventory expenses. Hy Shulman points out that these rough calculations are consistent with results from a cost study done as a part of the two-level maintenance concept evaluation in which avionics repair actions were relocated from base level to the depot and extensive use of commercial express transportation was made (see Fowler and Ste. Marie [1992]).

If these changes were appropriate to implement across weapon systems, further savings could be experienced from future buys for systems such as the C-17.

We are not insensitive to the concern that the relatively larger amount of inventory available in the current infrastructure serves to protect it from local failures of the logistics system. However, results discussed in Chapter Four suggest that the risk of reduced inventory levels is not as great as might be imagined.

Nor would an HVI in any way obviate the need for the readiness spares package (RSP). Readiness-spares-package assets will still be required to supplement peacetime operating stocks during wartime or other major contingencies. Those assets also play a role in protecting the system against local failures and one-time upsets. We anticipate that logisticians will continue to draw on RSP assets to ensure adequate performance of the fleet whenever the system breaks down and on those occasions when demands far outstrip routine resources.

Finally, we anticipate that savings from reduced inventory requirements would be experienced throughout the Air Force. For example, fewer parts would mean less overhead for storage. According to our calculations, an HVI might require only one-half the amount of storage space needed at FSLs and one-quarter the amount of space needed at PSPs. Depot storage under our analysis would also be reduced by roughly one-half.[21] In addition, since approximately 32,000 fewer assets would be needed under an HVI, we expect that some number of personnel positions associated with asset and in-

[21]Using Air Force data, we computed the floor space required to store all the assets allocated to each location, assuming items were stored packed for shipment. With a 50-percent density to allow for aisle space, and stacking boxes 10 feet high, the total requirement at all FSLs would be 509 square feet under the standard infrastructure and 261 square feet under the high-velocity infrastructure. The requirement at PSPs (Dover AFB and Travis AFB) would be 8,798 and 2,362 square feet, for the standard and high-velocity infrastructures, respectively. For the standard infrastructure, the bulk of each location's allocation is actually in the pipeline somewhere—not in a warehouse (i.e., those numbers represent worst-case storage estimates). For the HVI, a larger proportion of allocated inventory would tend to be on the shelves, since a larger proportion is safety stock. These estimates provide a feel for warehousing requirements but are not definitive.

Chapter Three

RESULTS FOR ALTERNATIVE SCENARIOS

In reality, things seldom turn out as planned. The C-5, like all weapon systems, encounters many unexpected circumstances. Results from our pilot study of the F-16 suggested that a high-velocity infrastructure would respond more quickly and with less overall degradation than the current infrastructure when faced with unexpected circumstances. But how would the infrastructure supporting the C-5 react to unexpected circumstances?

In this chapter, we present results from analyses of circumstances that diverge from those assumed in planning (i.e., those on which inventory levels are based). The scenarios we consider include the following:

- Inventory shaped in one year but used in another
- More-variable demand patterns than were planned for
- Small surge in operations tempo (like the support to operations in Somalia)
- Major operation (such as Operation Desert Shield).

We consider how each infrastructure would support operations if no adjustments were made to either the infrastructure itself or the stocks available in the system. In reality, each of these cases would be met by some adjustments on the part of Air Force logisticians and the logistics infrastructure. Our purpose here is to show the extent to which an HVI might decrease reliance on management adaptations or reserves by adapting more effectively to unexpected circumstances.

Although the effects of these stressing scenarios are felt by the entire fleet, management adaptations available at CONUS main bases tend to mitigate those effects. At en route locations, by contrast, management adaptations such as cannibalization are simply not available. The effect of an HVI on performance is generally most apparent at those locations. For our purposes, therefore, we consider the en route locations separately from CONUS locations.

EFFECT OF PROCUREMENT DELAYS WOULD BE REDUCED

A major perturbing factor in Air Force logistics is the delay induced by planning and procurement lead times. It is typical for the inventory available to the force in any year to have been shaped by decisions made several years earlier.

To explore the effect of such delays, we established an inventory position using the factors for parts recorded in the 1992 *Recoverable Consumption Item Requirements System* (D041) database,[1] then allocated that inventory to locations according to the requirement derived from the 1994 D041 database. Operation of the fleet was simulated using demand and repair-time factors from the 1994 D041 database. Inventory requirements were calculated independently for the standard infrastructure model (which is our model of the Air Force's current infrastructure) and the high-velocity infrastructure model. The amount of inventory available under the two infrastructures was vastly different ($481 million compared with $154 million for the standard and high-velocity infrastructures, respectively), as illustrated in Figure 3.1.

The pie charts in Figure 3.1 represent the dollar value of inventory that would have been owned by the Air Force had the 1992 requirement (as computed by us) been fully purchased. In 1994,

[1]Factors used include organization-and-intermediate-level demand rate (OIMDR), base not-reparable-this-station (NRTS) rate, base condemnation rate, quantity per application (QPA), base order-and-ship time (OST), depot repair-flow time, and depot overhaul condemnation rate. All of these factors may change from year to year for any part. Most typical are changes in the OIMDR (which is maintained as an eight-quarter running average to reduce its variation from one report to the next) and the base NRTS rate. Demand rates in all cases have been adjusted to reflect the effect of deferred maintenance.

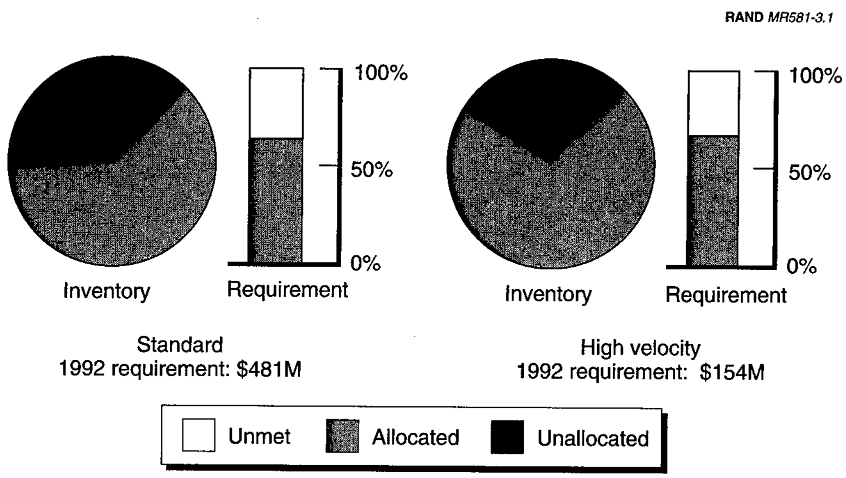

Figure 3.1—Utilization in 1994 of Inventory Established in 1992 (by value). More of the planned inventory is allocated under the high-velocity infrastructure.

some of that inventory would have been allocated to locations around the Air Force on the basis of then-realized demand patterns (lighter pie segments) and some would not have been allocated (darker pie segments). The bars in the figure represent the 1994 requirement for inventory (by value), as computed by us. The lower segment of each bar shows the proportion of that requirement that would have been met by inventory purchased in 1992. The upper portion of each bar shows the proportion of the 1994 requirement for which there would have been no inventory to allocate.

Under the standard infrastructure, 64 percent (by value) of the requirement determined with the 1994 factors was met by inventory procured with the 1992 factors, as seen in the left bar chart. Of that inventory, 60 percent of assets (39 percent of the value of the inventory) went unallocated because no requirement existed on the basis of the 1994 factors (unallocated inventory was removed from the analysis). Under the HVI, 66 percent (by value) of the requirement determined with the 1994 factors was met by inventory procured on the basis of the 1992 factors (right bar chart). Only 55 percent of 1992

assets (29 percent of the value) went unallocated on the basis of the 1994 factors.

Since, for both infrastructures, the inventory that would have been procured in the earlier year did not contain all of the assets needed in the execution year, it is not surprising to find that performance was degraded. The standard infrastructure starts off with a 43-percent shortfall in inventory assets, whereas the HVI starts off with a 35-percent shortfall. However, as those shortages are felt during operation, and replacements must be drawn from central stocks or generated through repair, it takes the HVI only a fraction of the time it takes the standard infrastructure to provide those replacements.

After a year of simulated activity, the fleetwide (that is, considering all aircraft) FMC+ rate under the standard infrastructure was 18 percentage points lower under these conditions than in the baseline case (Table 3.1).[2] Departure reliability was almost 6 percentage points lower. Under the HVI, the fleetwide FMC+ rate fell only 2 percentage points and the departure reliability rose 3 percentage points.

Under the standard infrastructure, CONUS main bases lost 30 percentage points of FMC+; Guard and Reserve bases lost 10 percentage points. By contrast, the drop at CONUS main bases was only 5 percentage points under the HVI, and Guard and Reserve bases saw a negligible improvement in FMC+ under the HVI.

Table 3.1

Change in Performance Measures When Planning and Execution Occur in Different Years

	Mission-Capable Status (percentage point)		Departure Reliability (percentage point)	
Base Type	Standard	High Velocity	Standard	High Velocity
CONUS Main	–29.8	–4.6	–3.6	0.0
Guard & Reserve	–10.0	+0.3	0.0	0.0
En Route	–4.2	+1.3	–7.3	+5.0
Fleetwide	–17.5	–1.7	–5.6	+3.0

[2]In all these comparisons, the baseline case is the case discussed in Chapter Two; that is, it is the case of peacetime operation under expected (planned-for) conditions.

For en route locations, the effect is shown in Figure 3.2. The FMC+ measure degrades over 4 percentage points for the standard infrastructure, whereas it improves slightly under the HVI. The effect on departure reliability is more dramatic: Departure reliability drops 7 percentage points in the standard case but improves 5 percentage points in the high-velocity case. Comparing degraded-performance figures directly, the HVI would perform roughly 6 percentage points better in the FMC+ measure and roughly 11 percentage points better in departures—which translates to 1,200 additional en route sorties completed annually by FMC aircraft under an HVI.

VARIABILITY OF DEMAND RATES IS LESS DAMAGING

One of the most fundamental observations in over 40 years of RAND logistics research has been that demand patterns are uncertain.[3]

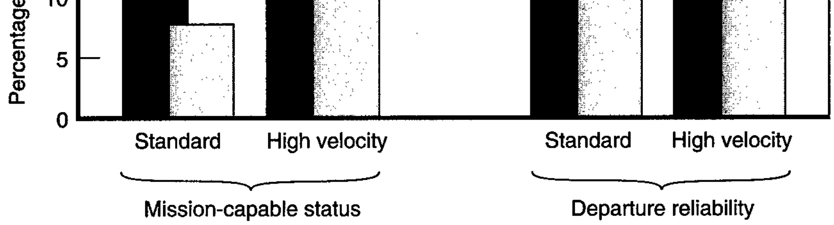

Figure 3.2—En Route Performance Measures When Planning and Execution Occur in Different Years. An HVI would protect against degradation due to inventory-adjustment delays.

[3]See, for example, the following RAND reports: Brown (1956), Pyles (1984), Hodges and Pyles (1990), and Adams et al. (1993).

Demands on the supply system arise in highly unpredictable ways, at highly unpredictable times. Nevertheless, the logistics system must rely on some demand predictions. A major part of the Lean Logistics undertaking is to find ways to limit the risk of faulty demand predictions.

To evaluate the effect of uncertain demand patterns on the standard and high-velocity infrastructures, we increased a parameter called the *variance-to-mean ratio* (VTMR), which is the ratio of the variance in a population of values to the mean of that population. Dyna-METRIC uses the VTMR parameter in determining the demand rate for individual parts. The higher the VTMR, the greater the likelihood that demands will occur well removed from their statistical mean. Variance-to-mean ratios as high as 50 have been observed for individual parts.[4]

We applied the VTMR value of 1.5 to all parts in the baseline case. That value was based on earlier, empirical RAND research on the nature of demand uncertainty (Crawford, 1988). To evaluate the effect of higher variability in demand rates, we applied the value of 8 to all parts. A VTMR of 8 for the entire population of parts is considered quite stressing.

Higher variability in demand rates generally degrades mission-capable status, as summarized in Table 3.2. Compared with the baseline case, mission-capable status would be 27 percentage points worse under the standard infrastructure and roughly 20 percentage points worse under the high-velocity infrastructure. Higher VTMR also leads to missed departures under both infrastructures, with the HVI having an advantage (down less than 1 percentage point as opposed to a 13-percentage-point reduction for the standard infrastructure).

CONUS main bases experience a more substantial drop in mission-capable status in the face of higher VTMR (down 42 percentage

[4]Crawford (1988) surveyed supply-demand activity for several types of aircraft (including the C-5) in an attempt to understand the extent and nature of demand variability. In part, he concluded that demand variability arises in ways that are not understood a priori, and perhaps cannot be. He found that many sources of variability are exogenous to the logistics system and are not subject to its control.

Table 3.2

Change in Performance Measures When Demands Are More Variable Than Expected

Base Type	Mission-Capable Status (percentage point) Standard	Mission-Capable Status (percentage point) High Velocity	Departure Reliability (percentage point) Standard	Departure Reliability (percentage point) High Velocity
CONUS Main	–42.1	–31.9	–20.4	–3.1
Guard & Reserve	–23.8	–19.5	–9.9	–5.1
En Route	–4.2	+3.3	–9.2	+1.9
Fleetwide	–27.5	–19.9	–13.1	–0.2

points under the standard infrastructure). The HVI attenuates that drop slightly (to roughly 32 percentage points), and has a stronger cushioning effect on departure reliability at CONUS main bases (3 percentage points worse compared with the standard infrastructure's drop of 20 percentage points).

As shown in Figure 3.3, mission-capable status at en route locations falls to 8 percent under the standard infrastructure and rises to 16

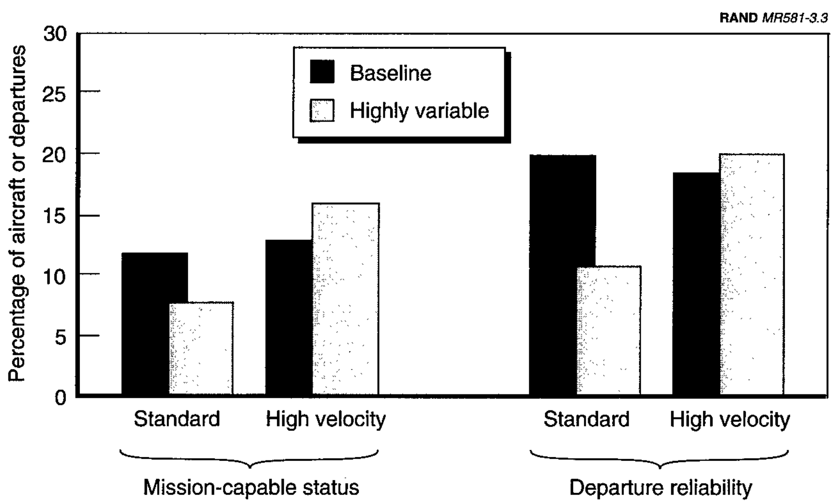

Figure 3.3—En Route Performance Measures When Demands Are More Variable Than Expected. When demand rates are substantially more variable than anticipated, an HVI adapts better than does the standard infrastructure.

percent under the HVI. Departure reliability would be 9 percentage points worse under the standard infrastructure, but would be slightly improved under an HVI.

The improvement in performance at en route bases under an HVI may be an artifact of the way Dyna-METRIC models VTMR. There is substantial room for debate about the proper interpretation of the variance in demand rates observed in the Air Force. The approach used here is consistent with that used in most other analyses: Variance in demand rates is assumed to arise from clustering of demands—a number of demands occur closely grouped in time, followed by a stretch of time in which there are no demands. Under this interpretation of the VTMR, bases with short pipelines and low demand rates will tend to do better when demands exhibit higher variability.[5]

SMALL-SCALE CONTINGENCY OPERATIONS ARE NOT STRESSING

In 1992, AMC supported U.S. military operations in Somalia through a temporary FSL it established outside Cairo, Egypt. Missions to Somalia were flown through the Cairo location, then to Mogadishu (where their cargo was off-loaded), then immediately on to a nearby intermediate staging location, and finally back to Cairo. At the Cairo location, necessary maintenance actions were taken, aircrews got required crew rest, and aircraft were refueled prior to returning to their home bases. More than 700 missions were flown in support of this contingency in 1992. This type and level of support are typical of AMC's peacetime tasking.

To test the effect of such small-scale operations on overall performance of the C-5 fleet, we duplicated the landing load created by the Somalia support effort, placing our hypothetical effort in the Pacific. In all, we increased the level of activity of the fleet by about 10 percent. Two additional aircraft—taken from the pool of untasked aircraft at Travis AFB—were dedicated to this effort.[6] *No additional*

[5]The treatment of VTMR in Dyna-METRIC and the effect observed here are discussed in more detail in Appendix A.

[6]See Table C.2 for the tasking of aircraft under this scenario.

stocks were provided to support the additional flying (normally, AMC would dedicate an RSP segment to such an operation). The baseline program was flown for a year. The surge was then implemented and was flown for 30 days. At the end of that 30-day period, performance under both infrastructures was checked.

Supporting such an effort would not create a burden on either the standard or the high-velocity infrastructure, as shown in Table 3.3. Fleetwide mission-capable status is virtually unchanged under both infrastructures. Departure reliability would rise slightly under the HVI, probably because of the increased number of aircraft flying missions under this scenario. As shown in Figure 3.4, en route mission-capable status and departure reliability would change slightly, if at all, under the standard infrastructure. Both measures appear to be slightly improved at en route locations under the HVI, again probably as a result of the increased number of aircraft in the en route portion of the system.

MAJOR OPERATIONS WOULD BE BETTER SUPPORTED

A major operation such as Desert Shield *does* create a significant burden on both infrastructures. To evaluate this case, we increased the flying program in accordance with that experienced by the C-5 fleet during Operation Desert Shield (Lund et al., 1993). This flying program required that nearly every "untasked" aircraft (active, Guard, and Reserve) be pressed into service. In addition, one-third of the flights (assumed to be training missions) at both Dover AFB

Table 3.3

Change in Performance Measures When Routine Surge Is Supported

	Mission-Capable Status (percentage point)		Departure Reliability (percentage point)	
Base Type	Standard	High Velocity	Standard	High Velocity
CONUS Main	+0.3	–1.7	0.0	0.0
Guard & Reserve	+0.6	+1.0	0.0	0.0
En Route	+1.1	+4.3	–0.6	+6.3
Fleetwide	–0.1	–0.0	–2.6	+1.8

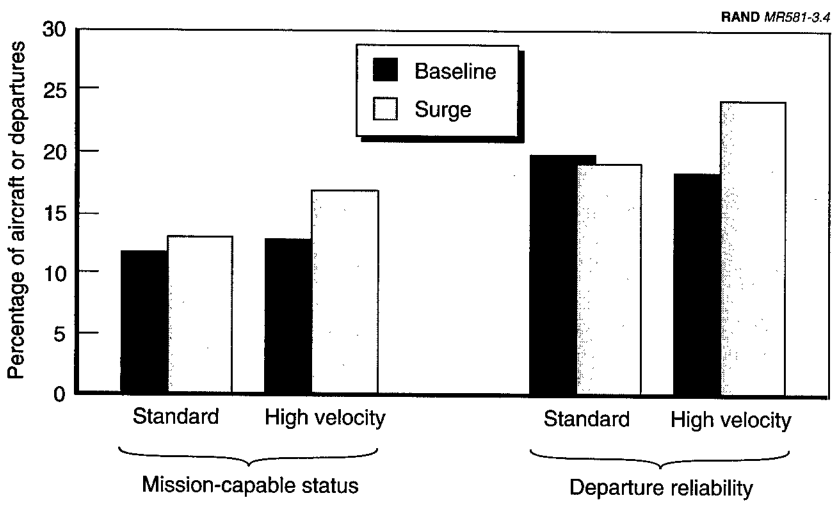

Figure 3.4—En Route Performance Measures When Routine Surge Is Supported. An HVI would feel the effect of a routine surge in tasking, such as support to operations in Somalia, less than the standard infrastructure does.

and Travis AFB were stopped.[7] Our hypothetical operation was placed in Southeast Asia, with Hickam AFB, Hawaii, Elmendorf AFB, Alaska, and (to a lesser extent) Anderson AFB, Guam, used as way-point staging areas. Roughly 1,900 landings per month were added to the flying program, increasing total flying by about 117 percent. Again, *no additional stocks were provided,* and inventory was not relocated in anticipation of the program. In reality, such an effort would involve substantial use of RSP assets.

The baseline program was flown for a year, at which time the major operation was started. After 30 days of that operation, both infra-

[7]We used our model for computing C-5 beddown (see "C-5 Operations and Support" in Appendix A and Table C.2 in Appendix C) to determine aircraft requirements for the increased flying program. In addition to tasking all in-service aircraft, two aircraft were moved from "depot-repair" to "active" status. Air Mobility Command personnel noted that this "beddown" matched their experience in Desert Shield remarkably well, including the movement of aircraft from depot to active status.

structures had difficulties keeping up with the increased load (see Table 3.4). Fleetwide mission-capable status fell 39 percentage points under the standard infrastructure in those 30 days. The precipitous drop at Guard and Reserve locations is to be expected, since all of the aircraft at those locations were activated to support the operation, leaving no untasked aircraft as a pool for cannibalization.

Figure 3.5 shows performance at en route locations. The increases in performance result from having more aircraft dedicated to the flying load en route. Taken literally, these results suggest that an HVI would produce over 200 more FMC sorties per month than would the standard infrastructure. It is important to reiterate, however, that adjustments were not made to either the infrastructure or the inventory levels. In addition, support for major operations may be limited primarily by the availability of flight crews—a factor we have not considered here.

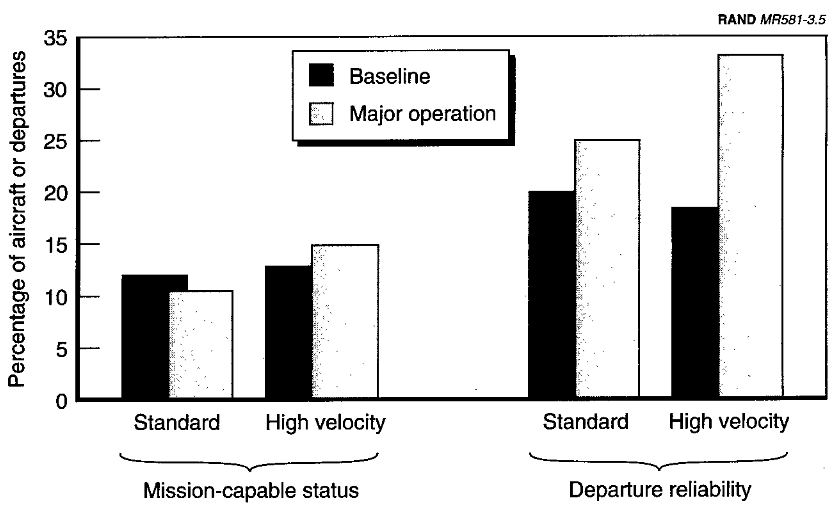

Figure 3.5—En Route Performance Measures in Response to a Major Operation. An HVI would provide greater capability than would the standard infrastructure during conduct of a major operation such as Operation Desert Shield.

Table 3.4

Change in Performance Measures When a Major Operation Is Supported

	Mission-Capable Status (percentage point)		Departure Reliability (percentage point)	
Base Type	Standard	High Velocity	Standard	High Velocity
CONUS Main	–14.0	–9.6	–1.9	–3.7
Guard & Reserve	–37.2	–27.0	–12.5	–5.0
En Route	–0.9	+2.0	+5.3	+14.9
Fleetwide	–39.2	–36.6	–12.0	–4.7

SUMMARY OF ALTERNATIVE SCENARIOS

- HVI is substantially less affected by spares-acquisition lead times than is the current infrastructure.
- HVI cushions the debilitating effect of variability in demand rates.
- Small surge has little effect on either infrastructure.
- HVI would support a major operation substantially better than would the current infrastructure.

The time lag between requirements determination and the availability of assets in the inventory generally limits aircraft readiness, since the number and mix of assets in the inventory are often at odds with supply needs at the time. When faced with inventory that does not match conditions that prevail during execution, an HVI would provide substantially better performance than would today's infrastructure.

More-variable demand patterns also degrade system performance. A great deal of variability arises naturally in the logistics system and cannot be predicted or controlled. When exposed to higher variability than anticipated, an HVI would adapt better than the standard infrastructure would, cushioning the effect.

The increased operating tempo of a small surge such as that experienced in support of operations in Somalia would have little effect on either the standard or high-velocity infrastructure. In response to a large surge, such as that required to support Operation Desert Shield,

an HVI would provide more fully mission-capable sorties than would the standard infrastructure.[8] As discussed in Chapter Two, the need for management adaptations in response to such stressing scenarios should be reduced under an HVI; the effectiveness of such adaptations should generally be increased.

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[8]There is room for debate about whether an HVI could be sustained during a major contingency, especially during the deployment phase. The airlift assets (both commercial and military) through which high-velocity movement of reparables is assumed to occur would be in high demand for the movement of troops and unit equipment during a deployment. Competition for airlift assets could lead to a shortfall in sustainment lift, and thereby to a slower infrastructure. See also "Transportation Cutoff Is a Minor Concern" in Chapter Four.

Chapter Four

RESULTS OF SENSITIVITY ANALYSES

In modeling the standard and high-velocity infrastructures, we have made a number of assumptions about the availability of resources and about the Air Force's ability to implement anticipated innovations. In this chapter, we look at the sensitivity of our results to some of those assumptions, asking the following questions:

- How would failure of express transportation affect an HVI?
- How would the limitations imposed by existing inventory affect performance?
- Would the system be placed at risk by slow or faulty implementation of Lean Logistics?
- Would the management adaptations of priority distribution and forward placement of stocks be less effective under an HVI than they are today?

TRANSPORTATION CUTOFF IS A MINOR CONCERN

Transportation of assets represents roughly half of the time reparable parts spend in the logistics pipeline under the current infrastructure. Hiring an express carrier to move assets, instantly cutting that portion of the wholesale pipeline from 30 to 2 days, seems very attractive. But commercial carriers are not a part of the military; they are not generally under military control. Accepting commercial carriers as an integral part of an HVI might pose a risk to logistics operations. Failure of those carriers to provide expected service could lead to reduced operational performance or capability.

Considering that risk in detail is beyond the scope of this study. What we can say is that the one thing that allows commercial carriers to perform in an attractive way—their huge base of commercial customers—should also make them relatively safe for military use, at least in peacetime. The volume of traffic that the Air Force would place with commercial carriers is likely to be a small fraction of those carriers' existing commercial volume. In essence, the Air Force can ride the back of commercial users, whose expectation of service will be no less stringent than that of the Air Force.[1]

Nevertheless, accidents, strikes, and natural disasters do happen. To gain some insight into the risk to an HVI if commercial express transportation were to be disrupted, we posit a total shutdown of all traffic within CONUS for 15 days.

The baseline program was flown for a year, then all transportation within CONUS was cut off for 15 days, then restored. Since transportation capacity is inherently unconstrained in these models, pent-up demand to move assets was immediately satisfied: All delayed moves were started immediately on the sixteenth day.

By the end of the 15-day transportation cutoff, fleetwide mission-capable status under the HVI had dropped off 2 percentage points. En route locations suffered the most, with a drop of 4.6 percentage points by the end of the cutoff. Figure 4.1 compares the evolution of fleetwide mission-capable status under the standard and high-velocity infrastructures. After transportation was restored, performance under the HVI returned to its pre-cutoff level within a week. Performance under the standard infrastructure took much longer to recover.

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[1]It could be argued that commitments under the Civil Reserve Air Fleet (CRAF) program, if CRAF were fully activated, could make commercial carrier assets unavailable for "routine" logistics resupply during a major conflict. If correct, this situation could pose a risk to support of non-engaged units and would require a military workaround during wartime. However, we do not currently find this argument compelling. Adequate commercial airlift assets appear to be available to meet wartime requirements *and* to support other, routine resupply needs (especially within CONUS), even with full implementation of CRAF. A comprehensive development of wartime application of Lean Logistics concepts is beyond the scope of this document. It is the subject of ongoing debate in both the RAND and Air Force logistics communities.

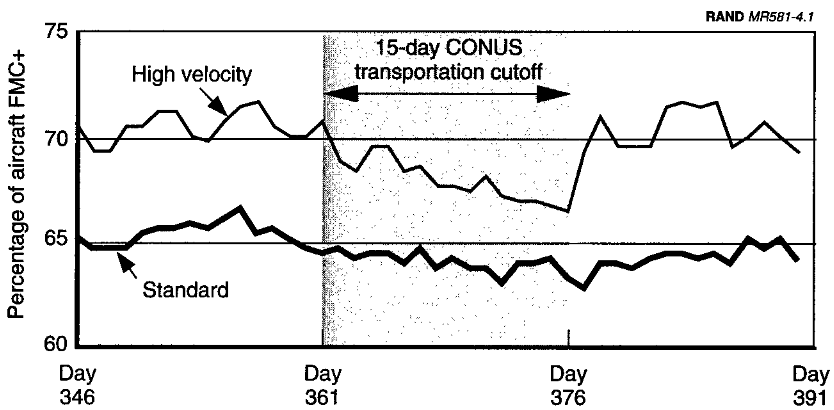

Figure 4.1—Fleetwide Mission-Capable Status During a Transportation Cutoff. Performance is degraded during the transportation cutoff, but an HVI would recover quickly after transportation is restored.

The overall effects of such a cutoff appear to be very small: A few aircraft are grounded, fleetwide, in either case.

EXISTING INVENTORY WOULD BE BETTER UTILIZED

Over time, the Air Force will reshape its inventory to fit a high-velocity infrastructure. However, in the near term, the Air Force will operate with the inventory it already owns. In all of the cases considered in this study up to this point, we have assumed an ideal situation in which assets are available to match the level set in the requirements computations for each location. However, the actual inventory of assets available in the logistics system is, in fact, a function of prior procurement decisions and budgetary limitations. None of the cases we have discussed so far have been constrained by inventory the Air Force actually owns or could afford to procure.

The D041 database contains information about the number of assets actually owned by the Air Force. To see how existing inventory might be utilized, we determined from the 1992 D041 database the number of assets for each item then owned by the Air Force as peacetime operating stocks. That inventory of C-5 parts was valued at approxi-

mately $911 million (replacement cost). We then allocated those assets to locations on the basis of the requirement computed for each infrastructure.[2]

As might be expected, the two infrastructures differ in their utilization of that inventory. Figure 4.2 compares the utilization of the inventory recorded in the 1992 D041 under the standard and high-velocity infrastructures on the basis of the replacement cost of items. The pie charts in Figure 4.2 show that the standard infrastructure had requirements covering roughly one-third (by value) of the assets in the inventory, whereas the high-velocity infrastructure had requirements covering less than one-fifth of that inventory. The remaining inventory was excess, in the sense that, in 1992, we did not have a requirement for it.

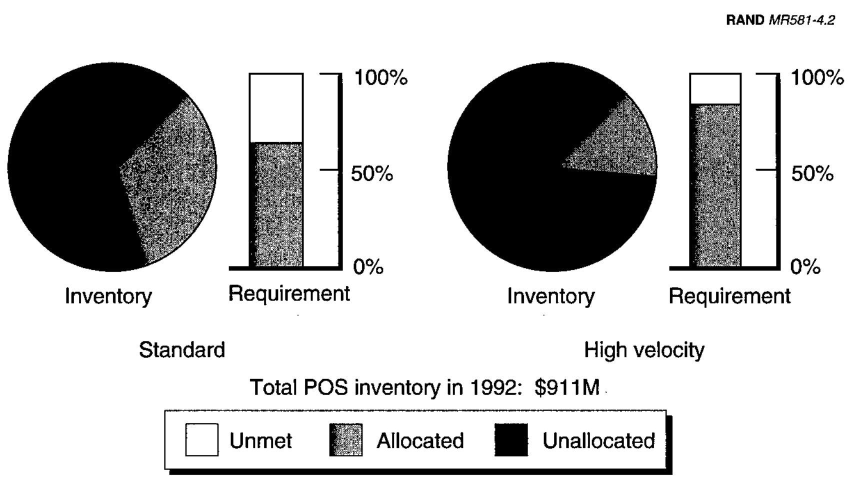

Figure 4.2—Utilization of 1992 Owned Inventory (by value). More of the requirement is met by existing inventory under the high-velocity infrastructure.

[2]Unallocated stock was considered ineligible and was not used for any purpose in these evaluations. Other sources of requirement against which POS assets are allocated have not been considered here. They may include Foreign Military Sales, use of these parts on other weapon systems, and programmed depot maintenance.

Looked at the other way around, we can ask how much of the computed requirement could be met by the inventory owned by the Air Force in 1992? As shown in the bar graphs in the figure, 62 percent of the computed requirement under the standard infrastructure was met from that inventory; 84 percent of the computed requirement was met under the HVI. The requirement under an HVI is smaller, so it is not surprising that we were more likely to find needed assets in the currently owned inventory in that case.

How would each infrastructure perform? As we expected, restricting each infrastructure to existing inventory has a detrimental effect on performance under the standard infrastructure. Since underlying demand rates are unaffected either by the choice of infrastructure or by the availability of assets, performance falls when there are fewer assets than were planned for. As shown in Figure 4.3, for en route bases,the effect is pronounced under the standard infrastructure. Fleetwide, degradation under the standard infrastructure is even more pronounced—mission-capable status would be 8 percentage points lower and departure reliability would be 4 percentage points lower. By contrast, both fleetwide and en route performance under

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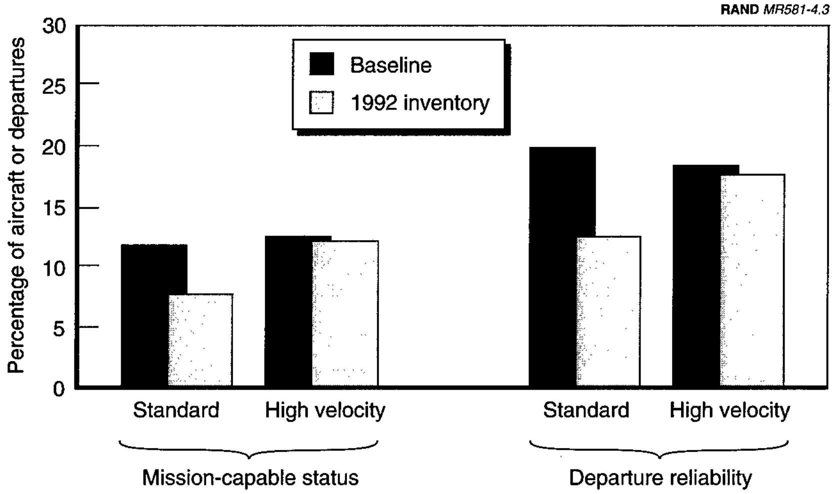

Figure 4.3—En Route Performance Measures If Only 1992 POS Inventory Is Used. Performance under the standard infrastructure is worse when inventory is limited, but remains almost unchanged under the HVI.

the HVI would be nearly unchanged by limiting the inventory used to only those assets owned by the Air Force in 1992.

UNCOORDINATED IMPLEMENTATION WOULD DEGRADE PERFORMANCE

During the transition to Lean Logistics, it is inevitable that some parts of the system will lag behind others in implementing improvements. If the Air Force were to make a total commitment to a high-velocity infrastructure—recomputing inventories, delaying or withdrawing procurements, and removing assets from circulation—how much risk to performance would there be?

In partial answer to that question, we established an inventory position on the basis of our most-optimistic assumptions about an HVI. We then simulated operation of the C-5 fleet at normal activity levels, assuming that various levels of improvement in infrastructure processes would be achieved.

Performance Would Be Affected

In Figure 4.4 we show the effect on mission-capable status of *partial* implementation of the assumed innovations, if inventory were reduced on the basis of *full* implementation of those innovations. We consider five levels of implementation:

None—no changes in infrastructure timing are achieved.

Express Transportation—transportation times are reduced from 17 days on average to 1 or 2 days through the use of commercial express carriers.

25% of Repair—25 percent of the anticipated improvement in depot repair-flow times is also achieved.

50% of Repair—50 percent of the anticipated improvement in depot repair-flow times is achieved.

All—transportation and depot repair times are reduced according to the assumptions in this study.

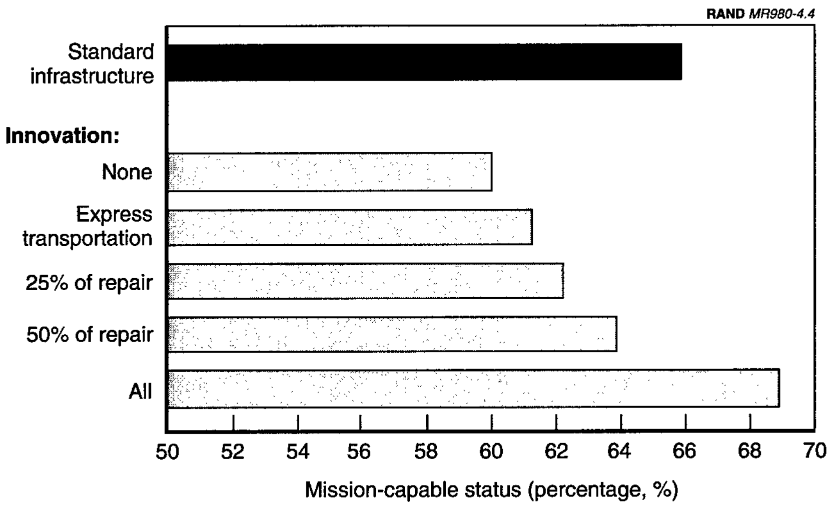

Figure 4.4—Mission-Capable Status with Various Degrees of Improvement. If improvements lag behind inventory reductions, some performance degradation will occur.

If all the assumed improvements are realized (bottom bar in the figure), the mission-capable rate for C-5s would exceed that achieved under the standard infrastructure (top bar), with all of its inventory, by several percentage points. If only express transportation and 50 percent of assumed depot repair improvements were achieved, but inventory levels were fully reduced, mission-capable rates would be a few percentage points lower than under the standard infrastructure.

Coordinating implementation of an HVI with current and anticipated inventory reductions will ease the transition. By removing inventory from the system slowly, under controlled conditions, and by sequestering removed inventory against the possibility of transition difficulties, the Air Force should be able to protect itself from much of the risk seen here. While uncoordinated implementation of Lean Logistics innovations could be damaging to performance, managing the transition to Lean Logistics should not be difficult.

Concerns About Repair Times Have Validity

Is there reason for concern that repair improvements might not be achieved? The Air Force Materiel Command (AFMC) is actively involved in reengineering depot repair processes to achieve the sort of speedup posited in this study. Substantial progress is being made. Here, we consider only one of many areas of concern: the scale of repair operations in each repair shop.

Implementation of Lean Logistics will not fundamentally change demand rates or demand patterns within the Air Force. The same number of parts will be broken each month, with or without Lean Logistics. The effects anticipated from Lean Logistics will come from rapid, reliable production of serviceable assets—to which depot repair is a major contributor. Any impediment to reduced depot repair-flow times could reduce the effectiveness of Lean Logistics.

One such impediment is that, when the scale of a repair operation is small, the random arrivals of parts for repair will tend to force either low utilization of personnel and other resources or long queues of parts awaiting repair.[3] Queues of parts imply longer in-process times—longer delays before parts will be available for issue to users.

To gain some insight into the risk this effect might pose, we looked at repair data from D041. We grouped parts together according to their Federal Supply Classification (FSC) and their source of repair (SOR). Assuming these groupings to be representative of individual repair shops, we computed the amount of work that would be seen at each such shop.[4]

Over 70 percent of the shops formed in that way would have an operating scale so small that there would be barely enough work to keep one person fully employed in each shop. A workload that small would be expected to lead to two outcomes: Either large queues develop so that a constant pool of jobs is kept waiting for the techni-

[3]This is a standard result from queueing theory. See, for example, Gross and Harris, 1974.

[4]This otherwise rash approximation makes some sense in that FSCs tend to group together parts that have similar underlying technology—parts that have similar repair requirements. However, this is at best a gross approximation of the scale of operations within AFMC.

cian, or utilization of personnel and other resources is substantially reduced.

This suggests that transitioning many actual depot repair shops to Lean Logistics may be a difficult task in many cases. Reduced utilization rates for repair technicians and equipment, which effectively may prove not to be an acceptable solution. Alternatively, the scale of operation of depot repair shops could be increased, by consolidation and by cross-training of personnel, for example. However, in many cases such consolidation may not prove to be technically feasible.

PRIORITY DISTRIBUTION HAS LIMITED EFFECT

To determine which location would benefit most from the next-available serviceable asset and to direct that asset to that location, both AMC and AFMC attempt to distribute serviceables to users on the basis of perceived need. In the simulation results shown so far, we have always distributed serviceables on the basis of perceived need at the moment. This form of priority distribution is one of many management adaptations used by the logistics system to compensate when that system gets out of balance.[5]

Priority distribution adds complexity to the system, since we must keep track of the relative need of each user and must expend effort to control the distribution system. With express delivery, the value of such a priority system might be diminished. In this case, we ask, Would randomly selecting from among requesting users the one to

[5]The Uniform Materiel Movement and Issue Priority System (UMMIPS) is another form of priority distribution. Under that system, operational units are assigned a transportation priority on the basis of their organization and military tasking. In general, units of greater national importance (e.g., Air Force One) and units at greater operational risk are assigned higher priority. Our model, however, does not reflect UMMIPS priorities; prioritization reflected in the model occurs on a case-by-case basis. More broadly, it should be noted that Dyna-METRIC and other models based on Palm's Theorem (see, for example, Crawford, 1981) do not have the ability to represent transportation-capacity constraints and so cannot show the effects of a stratified transportation system such as UMMIPS.

receive the next available serviceable asset result in worse performance than selecting that user on the basis of perceived need?[6]

Figure 4.5 compares en route performance for the baseline case when serviceable assets are distributed on the basis of need and when they are distributed to a randomly selected requester. Priority distribution (as practiced by Dyna-METRIC) *is* beneficial to the standard infrastructure at en route bases (i.e., performance is worse without priority distribution). Although performance under the HVI for en route bases is better when users are randomly selected, fleetwide performance is worse under random selection, as shown in Table 4.1.

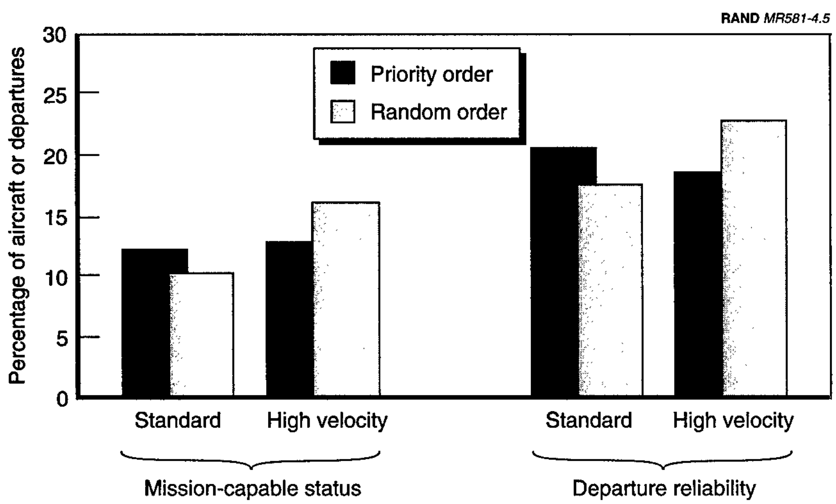

Figure 4.5—En Route Performance Measures With and Without Priority Distribution. Priority distribution is effective under the standard infrastructure, but may not be effective under the HVI for en route locations.

[6]Under certain conditions, a random-draw policy may be considered probabilistically equivalent to a first-come–first-served (FCFS) policy. "This equivalency exists when the expected mix of components arriving for repair [or ready for distribution] is constant over time. If the mix is not constant, random induction may be more likely to select a critical component (of which there probably will be more queued) than the component that has been waiting the longest" (Isaacson and Boren, 1993, footnote 1 on p. 7).

Table 4.1

Change in Performance Measures If Priority Distribution Were Not to Be Used

	Mission-Capable Status (percentage point)		Departure Reliability (percentage point)	
Base Type	Standard	High Velocity	Standard	High Velocity
CONUS Main	–0.9	+0.6	0.0	0.0
Guard & Reserve	–6.4	–9.4	0.0	0.0
En Route	–1.7	+3.3	–2.3	+4.0
Fleetwide	–3.0	–2.2	–1.3	+2.4

However, we must be careful not to overinterpret these results, which seem, at best, ambiguous. The demand rate for any part is likely to vary more *between bases* than our simulation accounts for. Priority distribution would be expected to have a greater effect under conditions of greater variability. FSLs in our model represent aggregations of actual en route locations in their service regions. On the one hand, these findings may understate the *potential* effect of priority distribution in the real world. On the other hand, Dyna-METRIC's near-perfect knowledge of the relative value of each part and its uniform application of prioritization mean that our results tend to overstate *actual* Air Force experience.

On balance, distribution on the basis of priority of need as judged by improvement in aircraft availability appears to be an effective tool today and will probably continue to be effective under a high-velocity infrastructure. Its value in practice may diminish as pipeline times are reduced.

FORWARD PLACEMENT OF STOCKS MAY NOT BE NECESSARY

Does the presence of forward-located stocks improve performance? The original impetus for this question was the speculation that express delivery might make the presence of such stocks unnecessary.

As Figure 4.6 shows, forward-located stocks improve performance under the standard infrastructure but may be detrimental to perfor-

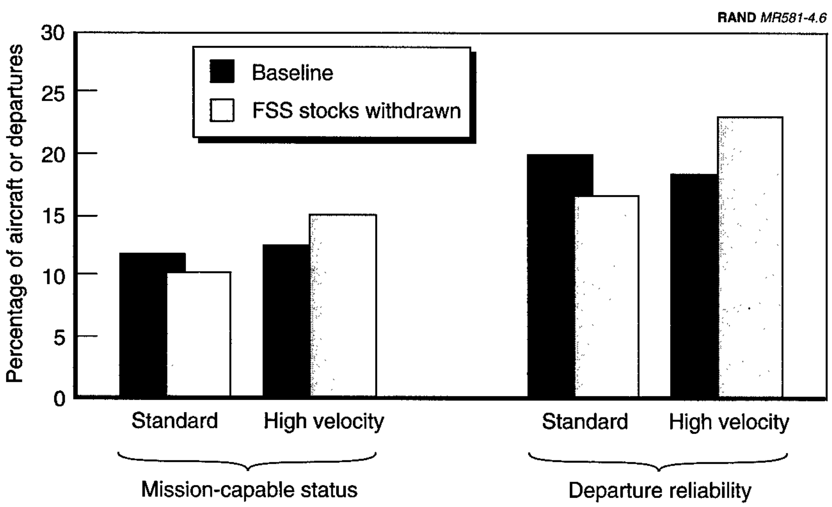

Figure 4.6—En Route Performance Measures With and Without Stocks at Forward Locations. Locating stocks forward aids performance under the standard infrastructure but does not improve performance under an HVI.

mance under an HVI. The effect of forward-located stocks is limited, because the parts grounding aircraft en route are often not the parts that warrant a forward-located level. That is, we are unable to predict with sufficient certainty which parts will be required at forward locations, so we are seldom able to have the right part at the right location when a demand occurs. Note that, in this case, all we have done is to move stocks originally allocated to each FSL back to that FSL's PSP. The same amount of stock is available; it is just located at a more central site, farther away.

Of course, we cannot argue for or against the forward supply system on the basis of this result alone. Many other factors must be taken into account: The FSS provides valuable support in the form of supply and maintenance personnel and information resources, in addition to providing a pool of serviceable assets. Forward supply locations also tend to be located at major bases, sharing facilities with other tenants on those bases. Many of the assets and resources used to support C-5 operations are available at those bases to support other weapon systems as well.

Nevertheless, results for this case do suggest that the effort expended in the management of forward-located assets would produce little value for the Air Force under an HVI.

SUMMARY OF SENSITIVITY ANALYSES

- A transportation cutoff in CONUS would slow, but not cripple, an HVI; the standard infrastructure would take much longer to recover from such a cutoff.
- HVI would make better use of current assets.
- Uncoordinated implementation of Lean Logistics would degrade performance under the HVI; the transition period will require management attention.
- Priority distribution may remain a useful management adaptation, but intensively managed forward stocks (i.e., FSLs) may not be as valuable under an HVI as under the current infrastructure.

A high-velocity infrastructure would rely heavily on commercial express carriers. Some risk would be faced if those carriers were unable to perform. For example, if transportation within CONUS were cut off for 15 days, performance under an HVI would degrade, reducing aircraft availability by perhaps two aircraft fleetwide. Approximately the same degradation would be felt under the standard infrastructure. Yet, whereas performance under the high-velocity infrastructure should recover within days once transportation was restored, performance under the standard infrastructure would probably take weeks or more to recover.

When limited to the assets actually owned by the Air Force in 1992, an HVI would support virtually the same performance as planned for. The standard infrastructure, on the other hand, would support only about 87 percent of the FMC+ aircraft it was planned to support.

The Air Force would face some risk if the implementation of Lean Logistics proceeds at an uneven pace and inventory reductions are taken in anticipation of procedural improvements that do not materialize. For example, if only the shift to express transportation takes place (i.e., no depot improvements occur), as many as 8 fewer FMC+

aircraft could be supported (although departures would be unaffected). However, the transition to Lean Logistics can be managed: No-longer-needed assets can be removed from the system slowly and can be held in "cold storage" against a possible future need.

Finally, priority distribution of assets and forward placement of stocks at the FSLs might prove to be unnecessary under an HVI. Priority distribution will probably continue to have some merit under an HVI, although its benefit should be reduced. However, placement of stocks at the FSLs may prove to be less effective under an HVI than currently expected. Moving those stocks back from the FSLs to their supporting PSPs would allow better use of the assets, since direct distribution to the needing location can be accomplished rapidly. Forward supply locations may remain important to AMC for other reasons, however.

Chapter Five

CONCLUSIONS

- It is possible to model logistics aspects of the C-5 Galaxy using existing tools.
- That process is arduous; existing tools are largely inadequate.
- AMC's LG community does not routinely gather and maintain the data needed to support this sort of analysis, although that situation appears to be improving.
- A high-velocity logistics infrastructure would provide more-robust performance for the C-5.
- A high-velocity logistics infrastructure would result in modest but real budgetary savings from reductions in the inventory requirement, especially over the long term.
- AMC's FSS is currently fairly lean; little improvement in performance as a result of changes in the FSS should be anticipated.

Initially, there was some skepticism about the effectiveness of simulation as a way of understanding the operation and support of the C-5 Galaxy. Air Mobility Command pointed out that prior Air Force efforts to model this aircraft had produced results that were often misleading and that unfairly assessed AMC's support efforts. An initial task in this study, therefore, was to generate a credible model of C-5 operation and support.

Such a model has been produced. It provides a reasonable approximation of Air Force experience in operating and supporting the C-5.

It also demonstrates the difficulties inherent in such an analytic effort. Modeling the C-5 using existing tools proved to be an arduous task, in large part because those tools are not equipped to support many of the circumstances we have seen in this study: flying from place to place, low number of aircraft per location, low flying rate per aircraft, widely dispersed operations (which create a requirement for widely dispersed support), and a highly resilient aircraft—one on which substantial amounts of maintenance can be deferred. The C-5 (and, we suspect, many other large aircraft) does not perform logistically like fighter and bomber aircraft, for which considerable analytic experience has been accrued.

The process of developing our model of C-5 operation and support was further complicated by AMC's lack of experience in gathering and maintaining the volume and type of information needed. Its management of information (particularly its use of SBSS data) improved remarkably during this study.

Ironically, AMC has been forced by the very circumstances under which the C-5 operates to develop a relatively high-velocity infrastructure of its own. In order to deal with many of the same stresses and uncertainties that Lean Logistics is addressing for the Air Force at large, AMC has found it necessary to implement many Lean Logistics concepts already. We are hopeful that that trend will continue and that other organizations within the Air Force will learn from AMC's experience.

A high-velocity infrastructure, having transportation times of 1 or 2 days and wholesale repair-flow times similar to hands-on repair times, would support C-5 performance that is the same as or better than what the current infrastructure provides, across a wide range of conditions and circumstances: inappropriate inventory, greater variability in demand rates, large increases in operating tempo, and a cutoff of transportation within CONUS.

Such an infrastructure would better protect the Air Force from the debilitating effects of most unanticipated circumstances. Perhaps more important, because such an infrastructure presents users and managers with a more rapid *and more reliable* logistics system, the need for management interventions and adaptations (such as canni-

balization) should be reduced. At the same time, when such interventions are needed, they may turn out to be more effective.

To produce the same operational performance, a high-velocity infrastructure would require only one-sixth the amount of inventory—with one-third the value—required by the current infrastructure. Little, if any, budgetary savings should be anticipated in the short term. Reductions in inventory requirement can be realized only over time as new weapon systems are introduced or as the amount reinvested in existing inventory each year is reduced. If the inventory requirement were to be reduced as anticipated in this study, expenditures ascribable to inventory turnover ("churn") might be reduced by as much as $32 million annually. The anticipated reduction in pipeline inventory should also lead to reductions in management and information-system overhead.

Appendix A

MODELING THE C-5

In this study, we looked extensively at reparable components on the C-5 Galaxy airlifter, exploring how changes in the logistics infrastructure might translate to changes in operational capability for the C-5 fleet. Neither the Air Force nor RAND has had much experience with comprehensive analysis of logistics aspects of the C-5. Personnel at AMC felt that prior Air Force efforts had resulted in inaccurate and misleading findings. They were skeptical that a representative and comprehensive analysis could be successfully undertaken.

It would be impractical to undertake this sort of comprehensive analysis on the basis of field observations and experiments alone. The C-5 fleet is tasked and operated in small numbers—many taskings occur under unique circumstances. Establishing direct comparisons of C-5 operations for the purpose of evaluating potential logistics innovations would be difficult for the most favorable cases and simply infeasible for the majority of cases.

Extensive, comprehensive analyses of logistics innovations can be undertaken using simulation models. For many years, the Air Force has used Dyna-METRIC to explore the relationship between logistics policies and operational capabilities (see "Simulation" later in this appendix). Developed by RAND in the mid-1980s, Dyna-METRIC is an analytic tool for gaining an understanding of the implications of logistics-system alternatives for military capability. Two versions of Dyna-METRIC are in common use: an analytic version, which is based on direct interpretation of mathematical equations, and a version that uses Monte Carlo–based, discrete-event simulation. For

this study, we used the latest simulation version of Dyna-METRIC, Version 6.4.

Each of the 18 experimental cases considered in this report involved side-by-side comparison of simulation results for that case with simulation results for the standard (current-infrastructure) case. Simulations included 109 aircraft, consisting of 1,908 reparable line items, located at 20 bases, for at least 360 days of operation. Resulting statistics were gathered over 10 independent trials for each simulation. For comparison (as an illustration only), we can think of each case in this study as comparing the results from observing 10 independent and complete C-5 fleets operated for a year under the current infrastructure with the results of observing another 10 independent and complete C-5 fleets operated for that same year under a different logistics system.

In this appendix, we describe the way we have modeled C-5 operation and support. The following section describes C-5 operations as they occur and as we have modeled them. Using Dyna-METRIC to model C-5 operation and support proved to be more difficult than anticipated. Dyna-METRIC was originally developed with fighter and bomber aircraft in mind. Those aircraft typically operate out of fixed locations, flying from their home base to a combat region and then returning back to their home base. As a result, Dyna-METRIC does not model the movement of aircraft from location to location. In order to use Dyna-METRIC to study the C-5, we had to develop an approximation of C-5 operations (in which C-5s fly from one base to another) that accommodated Dyna-METRIC's underlying assumptions (in which aircraft operate out of fixed locations).

Next, we describe the way we have modeled reparable-part characteristics. Most data come from Air Force Materiel Command's (AFMC's) D041 data system; however, part-demand rates have been modified to reflect the fact that considerable maintenance and supply activity is deferred from en route (overseas) locations to home bases: Demand rates at those two sets of locations tend to be considerably different.

The two infrastructures examined in this study are described next; they assume different component-part repair times and differ in the time it takes to move a reparable component among locations. The

network of locations and their interconnections is the same in the two infrastructures: a total of 20 bases are connected with 6 intermediate component-repair facilities and with a single depot complex.

The amount of stock available at each location is then discussed. In modeling the C-5, we have computed the inventory requirement for each location in the same way the Standard Base Supply System (SBSS) does.

Finally, we discuss the way Dyna-METRIC has been used to simulate C-5 operations and some of the difficulties we encountered in that process.

C-5 OPERATIONS AND SUPPORT

In Practice

The C-5 Galaxy airlifter operates out of 6 home bases, all within the continental United States (CONUS). Active-duty C-5s are operated by Air Mobility Command (AMC) out of Dover AFB, Delaware, and Travis AFB, California; and by Air Education and Training Command (AETC) out of Altus AFB, Oklahoma. Air Force Reserve C-5s are operated out of Kelly AFB, Texas, and Westover ARB, Massachusetts. Air National Guard C-5s are operated out of Stewart International Airport, New York.

USAF Fact Sheet 92-35, *C-5A/B Galaxy*, states that "The C-5 Galaxy is a heavy-cargo transport designed to provide massive strategic airlift, for deployment and supply of combat and support forces" (USAF, 1992a). The mission of the C-5 takes it along extended routes: A typical mission, which may take several days to complete, involves flying from home base, stopping at several remote locations en route, then flying back to home base. Table A.1 summarizes C-5 landing activity for 1992.[1] Of the over 18,800 landings that occurred at a total of over 400 locations during 1992, 39 percent were at home bases (some of which were for en route, training, or maintenance-related flights). In all, C-5s landed at remote locations 1.6 times for every time they landed at a home base.

[1]Data on landing activity for 1992 were provided by HQ AMC.

Table A.1

Summary of C-5 Landing Activity for 1992

Region	Locations	Landings	Landings per Location
CONUS	200	11,615	58
Europe	54	2,284	42
Pacific	18	1,272	71
Pacific Rim	14	899	64
Africa	18	894	50
Southwest Asia	23	846	37
Central and South America	32	693	22
Asia	5	95	19
South Pacific	11	80	7
Canada	16	64	4
North Atlantic	3	34	11
Former USSR	5	33	7
Home Bases	6	7,276	1,213
Other	400	11,530	29

SOURCE: HQ AMC/LGS and LGQ, private communication, 1993.

To support these widely dispersed operations, AMC runs an extensive supply network. With just over one-third of its flying operations overseas, AMC's forward supply system (FSS) is a crucial part of its logistics infrastructure. For the C-5, the FSS consists of two primary supply points (PSPs), one at Dover AFB and another at Travis AFB; eleven forward supply locations (FSLs); and a handful of forward supply points.[2] Table A.2 lists these major operating locations and summarizes the C-5 landing activity they supported throughout 1992.

Major maintenance actions and primary stock warehousing occur at the PSPs. Significant aircraft maintenance capability also exists at the FSLs, which are located at major overseas Air Force operating bases. The PSPs provide logistics support (including component repair) to the FSLs, which, in turn, provide supply and maintenance support to locations in their geographic regions (but do not generally have any component-repair capability for C-5 components).

[2]The forward supply points were being phased out of the FSS at the time of this study.

Table A.2

Landing Activity at Major Locations in 1992

Location	Region Served	Locations Served	Landings in Region
Home			
Dover AFB, DE	Europe, Africa, Western Hemisphere	1	3,157
Travis AFB, CA	Pacific, Asia, Western Hemisphere	1	2,370
Altus AFB, OK	self	1	850
Kelly AFB, TX	self	1	450
Stewart IAP, NY	self	1	128
Westover ARB, MA	self	1	321
En Route			
Rhein-Main AB, FRG	Europe, W. Asia, Africa	49	1,606
Ramstein AB, FRG	Europe	11	469
Mildenhall AB, UK	Britain	11	268
Cairo(West), Egypt	Somalia Operations	6	739
Torrejón AB, Spain	Mediterranean	13	567
Lajes AB, Azores	self	1	231
Incirlik AB, Turkey	Middle East	7	109
Elmendorf AFB, AK	Alaska	8	413
Anderson AFB, Guam	self	1	222
Hickam AFB, HI	Central Pacific	22	732
Yokota AB, Japan	Asia	9	571
Kadena AB, Japan	Pacific Rim	9	458
Other	Western Hemisphere	254	5,145

SOURCE: AMC database of landings for 1992.

In addition to "routine" peacetime operations, Air Force operations in support of lesser contingencies are usually being conducted, for which AMC's services are required. For example, the United States conducted operations in Somalia throughout 1992, first to support humanitarian ends and later in an attempt to enforce peace in the region. Air Mobility Command provided an air bridge into the region throughout that contingency. Airlifters flew from locations in CONUS and Europe to a temporary FSL located outside Cairo, Egypt, known as *Cairo (West)*. From there, missions were flown into Mogadishu, Somalia, off-loaded, and immediately flown on to one of several intermediate-landing sites outside the conflict region. The planes were refueled at those sites, and any required major maintenance actions were taken. They then flew back through Cairo (West)

on their way home. Non-essential maintenance was deferred to either Cairo (West) or home base.

To support the additional traffic required for such operations, AMC allocates a portion of a readiness spares package (RSP) tailored to the amount of traffic and number of aircraft expected (these are formally called RSP *segments*). For support to operations in Somalia, the temporary FSL at Cairo (West) was allocated an RSP segment from Dover AFB.[3]

In the Model

A major challenge in modeling C-5 activity has been the mismatch between the assumptions made by Dyna-METRIC about activity patterns and the activity patterns we observed for the C-5.

In Dyna-METRIC, aircraft are assumed to fly from their home base to a target area and return to their home base without stopping along the way. In contrast, C-5 aircraft stop en route as part of each mission, generating significant maintenance and supply activity away from their home bases. This activity turns out to be difficult to model in Dyna-METRIC. We have addressed this problem by modeling the C-5 fleet as if aircraft were permanently located at the 6 main CONUS bases, the 11 FSLs, the Cairo (West) location, and at 2 made-up locations with which we represent other Western Hemisphere activity that is not part of the FSS.

Air Mobility Command did not have an estimate of the number of aircraft normally flying in each of the FSL service regions. We developed a simple model that enabled us to estimate the number of aircraft supported in each region on the basis of the number of landings in the region and some assumptions we made about the number of bases visited on a mission, the length of a mission (in days), and the likelihood that a mission would require a crew rest period (adding a

[3]We do not explicitly model RSP in this study. When computing stockage levels for Cairo (West), we merely computed a requirement for Cairo (West) as we did for any other FSL. That inventory requirement almost certainly did not match the assets in the RSP segment actually located at Cairo (West). When Air Force–owned assets were considered later in this study (see Chapter Four), Cairo (West) competed along with all the other locations for the assets that were available.

day to the mission). The beddown thus developed was checked by AMC for reasonableness, but it could not be validated because of the lack of AMC data. Table A.3 presents the assumptions used and the

Table A.3

Modeled Beddown and Activity Levels

Location	ICAO Code	Total Landings[a]	Percent of Missions Requiring Rest	Stops per Mission	Days per Mission	Landings per Day	Tasked Aircraft	Untasked Aircraft	Sorties per Aircraft per Day
Dover AFB	KDOV	3,157	20	1	1	8.65	10	13	0.38
Travis AFB	KSUU	2,370	20	1	1	6.49	7	10	0.38
Altus AFB[b]	KLTS	850				3.04	8	0	0.38
Westover ARB	KCEF	321	50	1	1	0.88	1	12	0.07
Kelly AFB	KSKF	450	50	1	2	1.23	1	17	0.07
Stewart IAP	KSWF	128	50	1	2	0.35	1	5	0.06
Rhein-Main AB	EDAF	1,606	80	2	3	4.40	3	0	1.47
Ramstein AB	EDAR	469	80	2	2	1.28	1	0	1.28
Mildenhall AB	EGUN	268	80	2	1	0.73	1	0	0.73
Cairo (West)	HECW	739	100	3	1	2.02	2	0	1.01
West (Dover)[c]	IDOV	2,939	20	2	2	8.05	5	0	1.61
West (Travis)[c]	ISUU	2,206	20	2	2	6.04	4	0	1.51
Torrejón AB	LETO	567	80	2	2	1.55	1	0	1.55
Lajes AB	LPLA	231	0	1	1	0.63	1	0	0.63
Incirlik AB	LTAG	109	80	2	1	0.10	1	0	0.30
Elmendorf AFB	PAED	413	1	2	1	1.13	1	0	1.13
Anderson AFB	PGUA	222	0	1	1	0.61	1	0	0.61
Hickam AFB	PHIK	732	1	2	3	2.01	1	0	2.01
Yokota AB	RJTY	571	80	2	2	1.56	1	0	1.56
Kadena AB	RODN	458	80	2	2	1.25	1	0	1.25

NOTE: ICAO is the International Civil Aviation Organization.

[a]Derived from AMC data; other values are assumed.

[b]The number of aircraft and activity level at Altus AFB were provided by AMC.

[c]These two "locations" represent other Western Hemisphere activity that is assumed to be serviced by either Dover AFB or Travis AFB.

resulting beddown produced for the baseline case in this study. Other beddowns used in this study are shown in Table C.2.[4]

The main AMC bases (Dover AFB and Travis AFB), the AETC base (Altus AFB), and the Guard and Reserve bases (Westover ARB, Kelly AFB, and Stewart IAP) each have a collocated repair facility (often called a *backshop*) for undertaking component repair. Other bases (i.e., the FSLs) are assumed in our model to have no repair capability; instead, they rely on the repair capability at their PSPs (that is, at Dover AFB and Travis AFB).

Within Dyna-METRIC, locations can be described in several ways. The BASE element in Dyna-METRIC has been used in this study to model flight-line activity. Hence, all operating locations are modeled as having a BASE. The CIRF element has been used to model air base backshops; those locations that have local repair capability are modeled as also having a CIRF. The aggregate of Air Logistics Centers (ALCs) and contractor facilities, which together provide wholesale repair and supply-management capabilities, is modeled using a single DEPO element. Hence, Dover AFB, which is both an operating base and a PSP, is modeled using a BASE element (KDOV) and a CIRF element (JDOV); Lajes AB, which is an FSL and has no local repair capability, is modeled using only a BASE element (LPLA).

No BASE in our model has repair capability (all repair parts are shipped to the serving CIRF for repair [in what is called *not reparable this station,* or NRTS, status—an action that is called a *NRTS action*]). Demand rates for parts were set according to whether the BASE at which the demand originates is a CONUS main base or not. Transportation links between FSLs and their PSPs (FSL BASEs and their associated CIRFs) and the links between backshops (CIRFs) and the depot system (DEPO) were set according to the study assumptions. The transportation link between backshops and collocated flight lines (CIRFs and their BASEs) was set at one-half day.

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[4]One shortcoming of this approach is that it assumes C-5 activity to be stable. In fact, C-5 activity is largely episodic; a large number of landings may be accumulated in a region over a short period of time, with very few landings occurring at other times. This suggests that the simulated results will tend to understate actual performance, since, at the very least, the actual system has foreknowledge of many upcoming episodes and can adjust the infrastructure to accommodate them.

Figure A.1 depicts the physical infrastructure as we have modeled it. As a shorthand, we have used International Civil Aviation Organization (ICAO) codes to identify locations (as shown in Table A.3). The codes used for CONUS bases begin with the letter "K." Each of the other locations represents one or more actual landing sites. For simplicity, all of the Air Logistics Centers and contractor sites that make up AFMC's wholesale repair and supply capability have been modeled as a single depot.

PART CHARACTERISTICS

Data Sources

We used the following designations and characteristics of reparable parts in this study:

- Federal Supply Classification (FSC)
- National Item Identification Number (NIIN)

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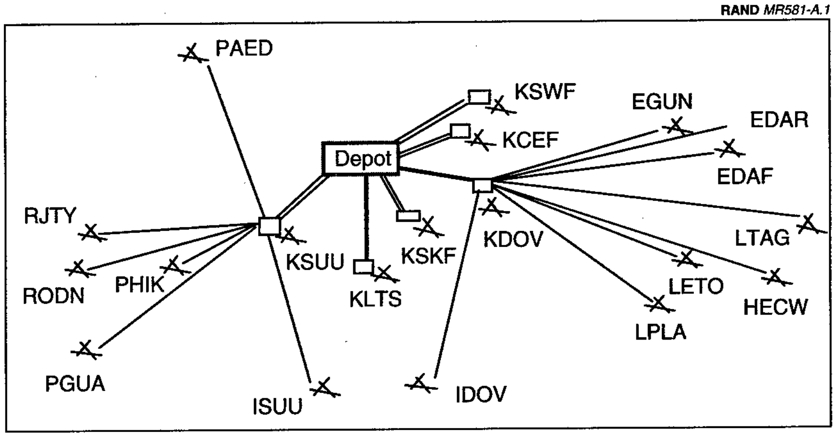

NOTES:
- Backshops (☐) modeled as CIRFs.
- IDOV and ISUU model Western Hemisphere activity not included in the FSS.
- Each non-CONUS flightline (✈) models activities at possibly many bases.

Figure A.1—Topology Modeled. The modeled locations are interconnected by the physical infrastructure shown.

- quantity per application (QPA)
- indenture level
- organization and intermediate–level demand rate (OIMDR)[5]
- base repair-cycle time
- base not-reparable-this-station (NRTS) rate
- base condemnation rate
- base order-and-ship time (OST)[6]
- depot repair-flow time
- depot overhaul condemnation rate.[7]

These data are recorded in the *Recoverable Consumption Item Requirements System,* better known as D041. That data system computes peacetime and war-readiness requirements for Air Force recoverable items. It maintains a comprehensive database of part characteristics to support those calculations. Demand-rate data are kept as an eight-quarter running average of demand history as reported by all users of each part. Hence, demand rates reported in D041 tend to smooth out seasonal and operational variation and to pool demand experiences for various types of aircraft.

Another source of demand histories is the Standard Base Supply System, through which supply accounting is performed at operating locations. This data system keeps a record, for each operating unit, of the number of demands on supply experienced by a unit for a part over the course of a year. In fact, these data, gathered from all operating units, serve as the basis for the data found in D041.

[5]Organization and intermediate–level demand rate (OIMDR) is recorded in D041 as demands per 100 flying hours. AMC prefers to account for demands on a per-sortie (per-landing) basis. We converted the D041 figures by applying AMC's flying experience as of March 1993 to the landing data for 1992. If, in aggregate, the flying thus represented is comparable to the flying completed in 1992 (as was argued by AMC), C-5s would have been completing roughly 4.02 flying hours per sortie.

[6]The order-and-ship time was used for both the forward movement of serviceable assets (which it is intended to represent) and the retrograde movement of carcasses.

[7]The overhaul condemnation rate was used as a surrogate for the depot condemnation rate during normal depot repair.

Because of some misunderstanding of, and prior dissatisfaction with, D041 data, personnel in AMC were reluctant to accept the part characteristics found in D041 as appropriate for this study. Unfortunately, they had SBSS data on hand for only a small fraction of the parts we were considering. Therefore, we began this study by comparing retail demand histories (from SBSS data) with wholesale demand rates (from D041) for those parts and locations for which data were available.

As the study progressed, availability of data from AMC improved; we eventually received data from 14 out of 17 locations monitored by AMC, covering 1,240 of the 1,625 unique parts included in the study. Acceptance of D041 data by AMC also gradually improved as our comparisons demonstrated the general applicability of those data to this type of analysis. Table A.4 summarizes demands that were observed in SBSS and that were expected on the basis of the demand rate shown in D041. The mismatch between *observed* and *expected* demands that is apparent in this table is indicative of the concerns raised by AMC about use of these wholesale data; it was one of the early challenges we had to address. In the following discussion, we explore some of the potential causes for that mismatch.

Assumptions About Parts

An assumption examined in the early portion of the study was that component repair was being performed only at the CONUS main bases and not at FSLs. By and large, component repair involves the replacement of shop-replaceable units (SRUs) within line-replaceable units (LRUs). Hence, if component repair were being done at FSLs, we would expect to see demands for SRUs at those locations. The worldwide average demand rate for those parts (as shown in D041) would lead us to expect nearly 5,000 demands per year for SRUs across reporting FSLs. The SBSS records only 40 such demands.[8] Our analysis confirms that component repair is *not* generally being done at FSLs.

[8]In this section, this and subsequent comparisons of expected and observed demands are limited to those parts and locations for which AMC provided data. In Table A.4, locations excluded from these comparisons are shown in gray.

Table A.4

Observed and Expected Annual Demands[a]

Location	Indenture	Observed[b]	Expected[c]	Modeled
CONUS Main				
KCEF	LRU	2,732	673	811
	SRU	334	291	166
KDOV	LRU	9,693	7,083	10,063
	SRU	2,462	3,203	6,288
KLTS	LRU	n/a	1,872	2,676
	SRU	n/a	839	1,065
KSKF	LRU	2,171	966	1,374
	SRU	569	419	373
KSUU	LRU	7,636	5,297	7,298
	SRU	2,594	2,396	1,399
KSWF	LRU	200	251	353
	SRU	2	100	22
Other Western Hemisphere				
	LRU	n/a	10,529	7,459
	SRU	n/a	5,214	0
Eastern FSS (Served by Dover AFB)				
EDAF	LRU	1,079	3,580	2,390
	SRU	12	1,612	0
EDAR	LRU	456	1,012	600
	SRU	11	438	0
EGUN	LRU	n/a	551	329
	SRU	n/a	240	0
HECW	LRU	n/a	1,632	1,147
	SRU	n/a	723	0
LETO	LRU	138	1,244	774
	SRU	3	545	0
LPLA	LRU	35	463	262
	SRU	0	198	0
LTAG	LRU	21	200	100
	SRU	0	82	0
Western FSS (Served by Travis AFB)				
PAED	LRU	148	884	605
	SRU	0	390	0
PGUA	LRU	n/a	443	248
	SRU	n/a	184	0
PHIK	LRU	587	1,615	953
	SRU	8	716	0
RJTY	LRU	543	1,252	825
	SRU	4	548	0
RODN	LRU	227	982	633
	SRU	2	427	0

NOTES: Gray rows denote locations not reported by AMC.
n/a indicates data that were not available.
[a]Excludes parts for which AMC did not provide data.
[b]From AMC, L08 database as of March 4, 1994 (i.e., covering 1993).
[c]From D041 as of March 1992 and AMC database of landings for 1992.

Another initial assertion by AMC was that maintenance activity levels would be roughly equivalent throughout the world; we expected to see similar demand rates, conditioned on operating activity levels, at all locations. The data in Table A.4 suggest that supply activity at the FSLs is substantially different from supply activity at the CONUS main bases.

Figure A.2 compares the estimation error that results from assuming the worldwide average demand rate for LRUs at CONUS main bases (excluding support to the other Western Hemisphere locations) with the error resulting from making that assumption for FSLs. A substantial number of demands expected at FSLs are not seen there. That overestimate at FSLs is at least partially made up for in these data by an underestimate at CONUS main bases.

On further reflection, AMC confirmed that maintenance activity is often deferred when aircraft are en route. Maintenance that can be

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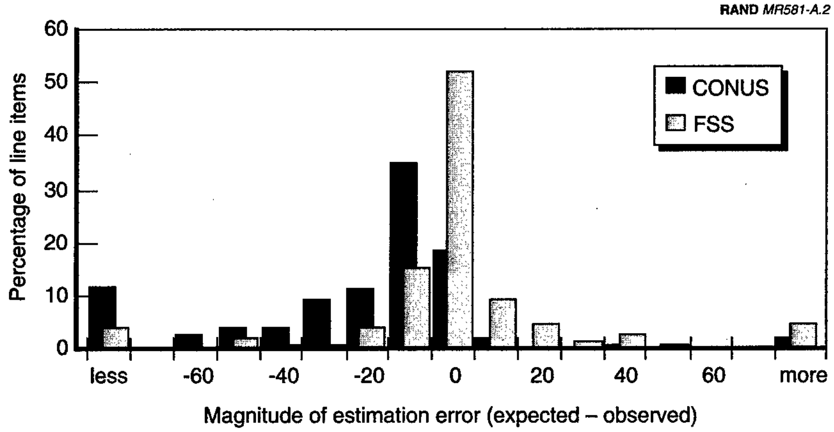

NOTE: Only includes observed LRUs at observed locations when there was either an observation or an expectation.

Figure A.2—Expected and Observed Demands. While fewer demands are observed in the FSS than the worldwide average would lead us to expect, more are observed at CONUS main bases than were expected.

deferred because of the existence of redundant, or backup, systems on the aircraft is routinely carried over to a more convenient time and location—usually at home base.

In the model, we accommodate this difference in level of supply activity by establishing two demand rates for each part: one that applies to CONUS main bases and another that applies to all other bases. Since there is substantial ambiguity about which parts experience deferred maintenance and to what extent, we established fairly restricted selection criteria:

> *If*
> observed demands were 75 percent or less of expected demands
> *and*
> more than two demands had been experienced worldwide,
> *then*
> we assumed that demands for the part in question were being deferred from en route locations to home base in proportion to the relationship between the observed and expected values.

The expected volume of demands worldwide was held constant; the source of those demands was adjusted between FSLs and CONUS main bases.

Finally, there was substantial doubt about the way in which activity at Western Hemisphere locations outside the FSS was being supported. AMC's initial hypothesis was that those locations were behaving just as locations in the FSS behave: routinely deferring demands from remote locations to home bases. Activity at locations outside the FSS was assumed to be supported by the CONUS main bases through lateral support actions (support one base provides for another, usually on a quid pro quo basis).

However, our comparison of retail (SBSS) and wholesale (D041) demand data suggests that this activity is not being supported through deferred maintenance *or* by lateral support from AMC bases. Referring to Table A.4, we would expect to see 11,232 demands for LRUs generated at FSLs, but we observe only 3,234 demands. Therefore, we can assume that roughly 70 percent of LRU demands expected to occur at FSLs are being deferred to home bases. At CONUS main bases, we would expect 14,270 demands for LRUs arising from activity at those bases, but observe 22,432 demands.

The 7,998 demands that are not observed at FSLs match reasonably well the 8,162 demands observed at CONUS main bases but not expected there.[9]

If other Western Hemisphere locations were acting like FSLs (as AMC initially hypothesized), we would expect them to be deferring LRU demands at about the same rate as the FSLs we observe in Table A.4. That is, they should be contributing about 7,370 demands for LRUs to the workload at the CONUS main bases (about 70 percent of their expected LRU demands). But this would result in many more demands at CONUS main bases than we observe; the data suggest to us that other Western Hemisphere locations are not behaving like locations in the FSS, and are most likely being supported directly by the depots or through lateral support actions that are not being seen by AMC.

After we discussed this finding with AMC, they suggested that these other Western Hemisphere locations be modeled as if they *were* being supported by the PSPs. Our inability to find evidence of that support in the SBSS data was believed to indicate a breakdown in current operating practices, not in AMC policy. An internal AMC study was undertaken to clarify operating practices and to determine actual sources of support for these locations.

The final column in Table A.4 shows the number of demands we used in developing the inventory requirement for the standard infrastructure (see "Allocation of Stock" below). In that requirements computation process, we mathematically simulated the prior year's demands on the basis of the demand rate for each part, the quantity of each part per aircraft, and the flying program at each location. The demand rate that resulted from that simulation is shown in the table under the heading "Modeled." Our rule for deferring supply actions from the FSLs to CONUS main bases is fairly conservative; we tend to overstate demands occurring at the FSLs and to understate demands occurring at CONUS main bases.[10]

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[9]This calculation does not include those demands from the unobserved FSS locations that are presumably also being deferred (probably about 1,800 demands).

[10]The imbalance at the two Reserve locations (Kelly AFB—KSKF—and Westover ARB—KCEF) was never fully explained, but may be a result of additional training activity undertaken at those locations.

We also identified, as a side effect of these calculations, a number of parts that displayed roughly the same demand rates at all locations. This information allowed us to establish a hypothetical minimum essential subsystem list (MESL), which is shown in Table C.11.[11] Those parts were considered "essential" in the modeling, and separate simulation runs were made to determine what aircraft availability rates would result if only those essential parts were required to be serviceable on the aircraft (see Chapter Two).

Resulting Part Characteristics

We originally identified 1,625 unique line items (NSNs) for inclusion in this study, using the following selection criteria:

- reparable items
- on (indentured to) the C-5 A or B model aircraft
- at the first or second level of indenture
- accounted for in terms of flying hours
- active in the inventory.[12]

There were 283 instances of ambiguous indenture relationships (the most common being a level 2 item indentured to multiple level 1 items). These ambiguities were resolved by creating "phantom" parts with their own unique NSNs and characteristics appropriate to their appearance in the indenture. The result was a parts list with 1,908 modeled line items.

We assumed that items appearing at level 1 in the indenture were line-replaceable units and that items appearing at level 2 were shop-

[11]Air Mobility Command did not have a MESL that was suitable for our use. We needed such a list so that we could compare the number of PMCS aircraft predicted by the model with the number experienced by AMC.

[12]Formally, we required that these be items listed in D041 under either the C005A or C005B mission-design series (MDS) with non-zero quantity per application (QPA), non-zero OIMDR, and with a PGMSEL code of 1. When an item appeared under both the A and B models of the C-5, we selected the most-stressing characteristics (e.g., the higher demand rate). This approach excluded such items as whole engines (and many engine parts), which are not indentured under the MDS.

replaceable units. This assumption is not always valid (sometimes level 2 items are actually LRUs), but more-definitive data were not available. A total of 967 LRUs and 941 SRUs resulted. For convenience, Table A.5 summarizes part characteristics as averages over the population of line items modeled. As we computed it, the average demand rate at CONUS main bases is more than twice that at other bases, reflecting the effect of deferred maintenance. The average replacement cost for an LRU is over $25,000, whereas the average replacement cost for an SRU is about $3,700. In the model, specific values for the characteristics shown in Table A.5 are used for each part: The averages in the table are shown as a convenient summary only.

LOGISTICS INFRASTRUCTURE

The logistics infrastructure supporting C-5 operations consists of the 11 FSLs, 2 PSPs, a network of depot and contractor facilities, and

Table A.5

Statistical Summary of Parts Characteristics (as modeled for the standard infrastructure)

	LRUs	SRUs
Total number	967	941
Repaired at ...		
PSP and depot	715	547
Depot only	252	394
QPA	2.67	9.06
Demands per landing ...		
CONUS main base	0.002699	0.001550
Other base	0.001057	0.000463
Base NRTS rate	99.58%	99.88%
Base condemn rate	0.42%	0.12%
PSP repair days	5.0	4.5
PSP NRTS rate	61.15%	81.03%
PSP condemn rate	0.42%	0.12%
Order-and-ship days	17.5	17.5
Depot repair days	53.7	46.1
Depot condemn rate	5.54%	4.59%
Depot repair cost	$4,018.75	$647.73
Replacement cost	$25,418.76	$3,684.35

transportation legs connecting all those locations. We modeled all of these elements (pooling all the depot and contractor facilities into a single depot), 1 AETC base, 2 Reserve bases, 1 ANG base, plus Cairo (West) and 2 "other Western Hemisphere" locations acting as additional FSLs. Outside CONUS, demands for parts originate at en route locations and are serviced by the FSL supporting the region in which they occur. In CONUS, demands occur either at one of the main bases (which have their own local supply and repair capabilities) or at other Air Force locations (which we model as being supported by the PSPs).

In this study we did not change the basic infrastructure; we changed the time it takes to exercise the various elements of that infrastructure.[13] A high-velocity infrastructure would aggressively reduce flow times for reparable components throughout the logistics process. In this study, we posited a high-velocity infrastructure that is at the optimistic edge of the feasible:

- next-day delivery of *all* depot-level reparables within CONUS
- 2-day delivery of *all* depot-level reparables overseas
- wholesale repair-flow times reduced to their "hands-on" repair times (akin to just-in-time, or JIT, repair), wherein Air Logistics Centers and their contract suppliers could implement what has been called "repair on demand."

Table A.6 (which repeats Table 2.1 from Chapter Two) illustrates the magnitude of those posited improvements. For transportation, we assumed overnight (express-carrier) delivery within CONUS, and 2-day delivery times from CONUS to en route locations. Current Air Force experience shows these times to be achievable for most items and to most locations, although they are a bit optimistic for out-sized and hazardous items, and for locations with unfavorable customs arrangements.[14] We assumed 2-day delivery for lateral support—a

[13]Some of the later excursions *do* consider alternative infrastructures as extensions of the present work (see Appendix B, "Tuning the Logistics System").

[14]More-recent (1998) experience with commercial express service to remote overseas locations suggests that 2-day service may still be optimistic. For example, service to Doha, Qatar, in 1998 averaged over 10 days.

Table A.6

Summary of Pipeline Segment Flow Times

Pipeline Segment	Flow Times for Respective Infrastructure: Current (days)	High Velocity (days)
Retrograde to PSP	8	2
Retail repair	2 to 7	2
Lateral support (i.e., TACC action)	2	2
Retrograde to depot	17	next day
Depot repair	54, average	7, average
Forward from depot	17	next day
Forward from PSP	4	2

NOTE: *Retrograde* is movement rearward, from an air base to or toward a depot. *Lateral* is movement from one air base to another. *Forward* is movement from a rearward location (e.g., depot) to or toward an air base.

mechanism we used to emulate the actions of the Tanker Airlift Control Center (TACC). Two days is in line with current experience.

For depot (wholesale) repair, we assumed that most repairs can be completed with a flow time that approximates the hands-on repair time for the item.[15] For some items, this assumption may be quite optimistic. Main landing gear tires, for example, are repaired (retreaded) under contract once a year. The average flow time is 153 days (almost half a year), even though the hands-on repair time is only a matter of hours. In Chapter Four, under the heading "Uncoordinated Implementation Would Degrade Performance," we suggest that the scale of repair operations for many items may be so small that substantial technical or policy changes will be required to achieve the times we posit. However, the effect of failing to achieve those times would not appear to be disastrous, as is shown there, in Figure 4.4. Further, while aggressive, our assumption does not ap-

[15]In this study, time spent awaiting parts (AWP) for non-reparable items (called "bits and pieces") was excluded from repair-flow times in all cases. Although data available to us were insufficient to support including bit-and-piece AWP time in our analyses, we note that bit-and-piece AWP time could prove to be a significant problem for a high-velocity infrastructure. Similarly, AWP times stemming from contractor delays and current AWP times not accounted for in the D041 record of flow times (neither of which could be modeled in this study) could put our assumptions about repair-flow-time improvements in jeopardy.

pear to be all that heroic for most items. We have allowed one day of flow time for each shift of repair effort invested in the "standard repair" of the item, corrected for weekends.[16]

Applying these assumptions results in a radical reduction in pipeline length. The weighted average pipeline delay (round trip, from removal at the aircraft, through repair at the wholesale or retail level, to serviceable and ready for issue) would be reduced from about 67 days under the standard infrastructure to about 8 days under a high-velocity infrastructure. We expect the primary effects on the logistics system to be as follows:

- Shorter pipelines respond more rapidly to changes in demand patterns.
- Shorter pipelines contain less inventory and therefore require fewer spares.
- Shorter pipelines simplify management processes.

Are These Assumptions Reasonable?

How reasonable is it to assume the use of commercial express transportation for reparable components? To answer that question we computed how many of each part we would expect to be shipped from and to each location, based on the same component-demand rates and NRTS rates used in our simulations. We then determined the weight and volume of those shipments, based on Air Force historical data on the weight and volume of each part packed for shipment.

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[16]Current pipeline times for the depots were taken from the March 1992 issue of the D041 database. All other current pipeline times were provided by AMC.

Data from a 1991 study of logistics support during Desert Shield (Crimiel, 1991) suggest that AMC's estimates for current pipeline times may have been optimistic. That study reports observed retrograde times to the Dover AFB PSP ("Retrograde to PSP" in Table A.6) averaging 8.6 days, Dover PSP repair times ("Retail repair") averaging 6.5 days, and order-and-ship times seen by Dover's FSLs ("Forward from PSP") averaging 18.4 days. That study also reports observed times for retrograde movement from Dover AFB to the ALCs ("Retrograde to depot") averaging 22.2 days, with order-and-ship times experienced by Dover AFB ("Forward from depot") averaging 19.1 days. Depot repair-flow times were not reported.

Almost all items we would expect to see shipped over the course of a year fall within the bounds of what an express carrier would consider "routine packages." Figure A.3 shows the number of shipments we observed in our simulation over the course of a year, expressed as weight (pounds) and volume (cubic feet). Weights up to 150 pounds would be considered routine; heavier items would require special handling. Similarly, packages of around 30 cubic feet could be handled as routine. While some items would require special handling (certainly some are classified, hazardous, or oversized), the vast majority of anticipated shipments appear to be well within express carriers' parameters.[17]

How reasonable is it to assume that component repair times can be reduced to near-hands-on times? To answer that question, we turned to D041. That database records the shop-flow time (the time

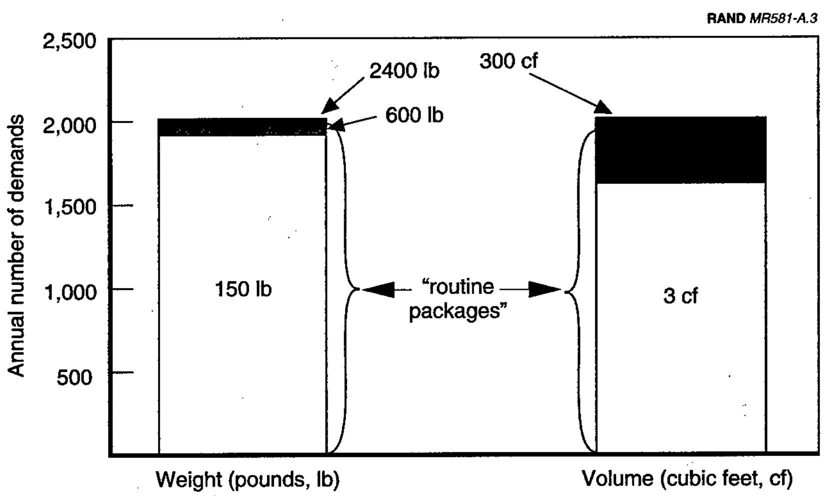

Figure A.3—Weight and Volume of Expected Annual Depot Repairs. Very few depot-repaired items will be too large for express shipment.

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[17]The weights and volumes cited are for items packed for shipment. To help visualize these volumes, consider that a package 16 inches on a side would have a volume of 2.4 cubic feet; a package 36 inches on a side would have a volume of 27 cubic feet.

it takes a part to move through a repair shop) and the "standard" repair cost, which we convert to hands-on repair time using a standard hourly billing rate, assuming single-shift, 5-day-per-week operation.

More than 80 percent of all items have hands-on repair times of less than 10 percent of their shop-flow times, as illustrated in Figure A.4. The horizontal axis of that graph shows the ratio of the hands-on depot repair time to the shop-flow time. The graph shows both the cumulative proportion of the population of parts (that is, NSNs, the thick line) and of expected demands (items to be repaired, the thin line). Notwithstanding the discussion in Chapter Four, under the heading "Concerns About Repair Times Have Validity," there appears to be substantial room for improvement in depot-shop-flow times.

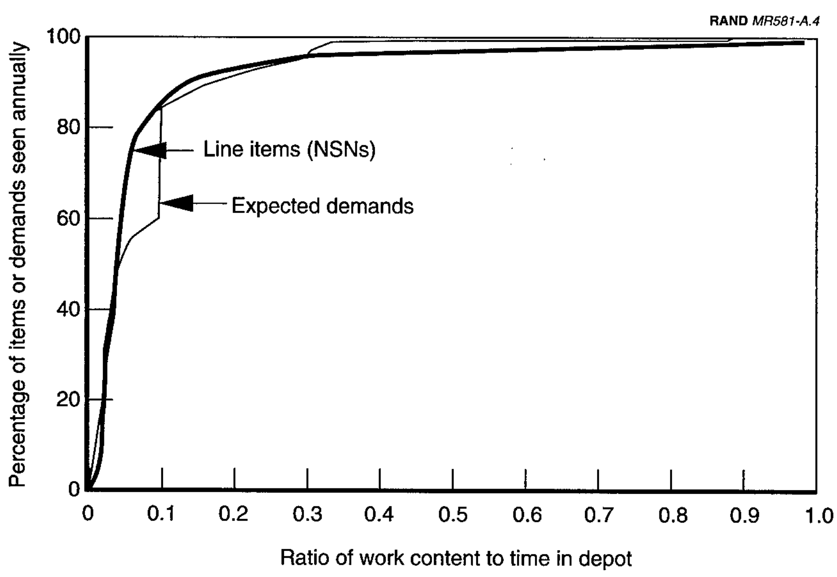

Figure A.4—Cumulative Proportion of Depot-Level Repair Items (or Work) Compared with the Ratio of Work Content Invested in Repair. More than 80 percent of items (or of demands seen in a year) spend less than 10 percent of their standard depot shop-flow time being repaired.

ALLOCATION OF STOCK

The process by which the Air Force allocates assets to locations is at best complex and obscure. In brief, each location accumulates a history of demands for parts, which serves as a basis for determining the allocations that will result for that location. Allocations occur in both a *planning* and an *execution* sense.

In this section, we discuss the way allocation decisions are made during planning—that is, when budgets are being set and contracts are being signed—and again during execution—that is when aircraft are being flown. We also discuss how we attempted to emulate those decision processes in our models.

Planning

For planning purposes, a level (referred to as the *requirement*) is established for each part at each location according to one of several methods of calculation. The level generally reflects the number of assets believed to be necessary to support an assumed activity rate at that location. It is based on assumptions about transportation and repair times, and the number of assets necessary to protect the location against unexpected surges in demand (called *safety stock*). Levels are recomputed periodically, depending on the policy being followed.

Understanding what such a *level* actually represents is complicated by several factors. First, the number of assets owned by the Air Force seldom agrees with the sum across all locations of the levels set for a part. Relative to the levels that have been established, the Air Force is usually either in "long" (too many) or "short" (too few) supply. Second, the level that has been set reflects not only the assets needed at the location itself but also assets that would normally be in repair at that location and in transit (to and possibly from the location, depending on the policy implemented by the calculation). Hence, a level of 5 for a part might reflect an assumption of, for example, 2 assets normally in transit to the location, 1 asset in repair at the location, and 2 assets expected to be on the shelf in supply at the location. In reality, the Air Force may be in short supply for that part; there may be only 3 assets available within the Air Force inventory corresponding to that level of 5.

When computing its requirement for peacetime operating stocks (POS), Air Mobility Command uses its recent experience as recorded in the SBSS.[18] Table A.7 summarizes the levels we would expect on the basis of demand rates, the levels actually recorded in SBSS accounts, and the levels we calculated for each location modeled. For main bases (PSPs, Guard and Reserve locations, and the AETC base serving C-5s), the SBSS demand-based calculation is the predominant source of AMC's POS requirements. For the FSLs, that calculation also predominates, but is modified to be slightly more generous.[19] (See the "Observed" columns in Table A.7.)

The nature of C-5 operations often causes demands to occur at locations not under AMC's direct control. In those situations, needed parts are provided by the FSL serving the region in which the de-

[18]This study considers only peacetime operating stock. We recognize that readiness-spares-package (RSP) assets are extremely important in both the planning and execution processes. However, limitations in the way Dyna-METRIC accounts for assets make it difficult to model AMC's use of RSP assets as a safety net during normal operations.

Excluding RSP assets from the study causes the mission-capable and departure-reliability rates shown herein to be somewhat understated relative to AMC experience (an effect we cannot currently measure, however). During normal Air Force operations, RSP assets are issued as needed and replenished on a priority basis. That ad hoc issuance of RSP assets is not supported by Dyna-METRIC. Excluding RSP assets causes the number of NMCS aircraft to be slightly smaller in reality than is reported by the simulation. Some situations in which aircraft are grounded in the simulation would actually have been resolved by the use of RSP assets (which would then be rapidly replenished by the supply system).

[19]The basic underlying calculation is described in the *USAF Supply Manual*, AFMAN 23-110, Volume II, Part Two, Chapter 19 (U.S. Air Force, 1992b; then called AFM 67-1). The variant of that calculation used for FSLs is described in AMC Supplement 8 to AFMAN 23-110, Volume II, Part Two, Chapter 19 (then called AFM 67-1; the issue we used was dated April 27, 1992). In these calculations, a part is qualified for a level when a threshold number of demands has been experienced in the preceding year. The fundamental difference between the two calculations (FSL and non-FSL) is that parts are qualified under Air Force policy on a location-by-location basis, whereas, under the AMC supplement, parts at FSLs are qualified on the basis of demands experienced throughout the FSS (i.e., the sum across all FSLs). The predominance of SBSS-based levels may change as other allocation methods such as Requirements-Based Leveling (RBL) are put in place.

mand arises, through lateral support. To ensure accurate recording of demand histories, AMC subsequently applies manual corrections to the SBSS accounts involved.

Table A.7

Inventory Requirements[a]

			Observed[c]			
Location	Indenture	Expected[b]	Demand-Based	Percentage (%)	Actual Level	Modeled[d]
EDAF	LRU	231	187	80	253	85
	SRU	0	8	82	10	0
EDAR	LRU	98	104	85	143	22
	SRU	0	5	100	5	0
EGUN	LRU	45	n/a	n/a	n/a	13
	SRU	0	n/a	n/a	n/a	0
HECW	LRU	123	n/a	n/a	n/a	44
	SRU	0	n/a	n/a	n/a	0
KCEF	LRU	72	353	35	592	97
	SRU	42	104	44	131	57
KDOV	LRU	1,918	972	33	1,530	1,580
	SRU	801	421	39	909	749
KLTS	LRU	179	n/a	n/a	n/a	254
	SRU	135	n/a	n/a	n/a	173
KSKF	LRU	99	331	71	519	15
	SRU	55	124	76	249	79
KSUU	LRU	1,362	1,013	36	1,650	1,177
	SRU	611	470	38	807	617
KSWF	LRU	28	65	80	99	56
	SRU	12	1	50	2	10
LETO	LRU	101	34	37	92	34
	SRU	0	2	100	2	0
LPLA	LRU	43	5	46	20	12
	SRU	0	0		0	0
LTAG	LRU	16	6	42	19	4
	SRU	0	0		0	0
PAED	LRU	73	43	75	58	22
	SRU	0	0		0	0
PGUA	LRU	33	n/a	n/a	n/a	8
	SRU	0	n/a	n/a	n/a	0

Table A.7—continued

			Observed[c]			
Location	Indenture	Expected[b]	Demand-Based	Percentage (%)	Actual Level	Modeled[d]
PHIK	LRU	135	106	70	177	37
	SRU	0	5	80	8	0
RJTY	LRU	98	111	72	172	28
	SRU	0	1	14	7	0
RODN	LRU	77	56	77	92	24
	SRU	0	1	50	2	0

NOTES: Gray rows denote locations not reported by AMC; *n/a* signifies that data were not available.

[a]Excludes parts for which AMC could not provide data.

[b]Computed by us on the basis of D041 demand rates; CONUS locations include the requirement computed for their backshops.

[c]From AMC, L08 database as of March 1994 (covering 1993); "Demand-Based" refers to the computation method used in this study; "Percentage" is the percent of line items using that method; "Actual Level" shows the actual level in effect at that location.

[d]Computed by us on the basis of modified D041 demand rates; CONUS locations include the requirement computed for their backshops.

Execution

In execution, the number of assets available may not be adequate to cover all requirements; actual assets on hand must be allocated to each location as needs arise. Even when the Air Force is not in short supply on some part, there may not be enough assets to go around because of the number of assets waiting for or in repair and because of maldistribution of assets caused by the movement of units from one location to another.

Assets are allocated during execution by estimating the relative benefit to each location of each asset, according to one of several approaches. For example, the Distribution and Repair In Variable Environments (DRIVE) approach considers the degree to which allocation of an asset to a location would improve aircraft availability at that location (Miller and Abell, 1992). We have allowed Dyna-METRIC to allocate each asset to requesting locations according to

Dyna-METRIC's ideal view of the potential improvement to aircraft availability.[20]

Model

Analytic estimates of inventory requirement are usually based on wholesale (D041) part data. These data, while a fair representation of the aggregate experience of AMC, turn out to be a poor model of detailed experience at AMC bases. Because of built-in redundancy and overall robustness of the C-5 aircraft, demands for many parts are deferred from the en route portion of the system to the PSPs. We were able to estimate the magnitude of deferred maintenance that was occurring and, hence, to have a basis for adjusting demand rates in the model by comparing estimates derived from D041 with reports from SBSSs.

We developed a requirements-computation program that emulates the calculations made by AMC. That program allowed us to vary several assumptions about the computation process (for example, the amount of safety stock at each location,[21] the way parts received for repair at PSPs [from FSLs] are accounted for, and whether variation is included in the simulation of historical demands).

The computation begins by creating a simulated demand history for each part at each location, based on the mean demand rate and an assumed variance in that rate for the part, and the historical activity (flying) level at that location (shown earlier in the "Modeled" column of Table A.4).

The program then uses that demand history to determine a required level of assets for each part at each location, as shown in Table A.7. That requirement is a function of the transportation and repair times

[20]The effectiveness of that level of allocation management is briefly considered in Chapter Four under the heading "Priority Distribution Has Limited Effect."

[21]The standard safety-stock calculation is $(3 \times p)^{1/2}$, where p is the pipeline quantity. The pipeline quantity is based on the demand rate, transportation times, and repair times for the part. Although detailed definitions vary, the *pipeline quantity* is basically the amount of stock required to cover expected demands for the period of time it is expected to take to receive a replacement from the wholesale or retail supply system to replace a broken part taken out of an aircraft. The safety stock is intended to provide a level of protection against the natural variation in arrival times of demands.

being assumed in any particular case.[22] It is also possible to specify to which locations the various segments of the total pipeline are to be allocated, which allows us to examine, for example, the effect of a fully centralized PSP system.

Most of the cases considered in this study assume that the calculated requirements are "fully funded," meaning that there are actual assets in the system corresponding to the required levels that were computed. In a few cases, we limited the number of assets in the system to those that were owned by the Air Force in 1992. For those cases, we allocated assets according to the computed levels, so that any shortage of assets would fall evenly on those locations that have the largest levels. Assets in excess of the computed requirement were noted and removed from the system.

For each case, we used data from D041 and other Air Force sources to compute the dollar value, shipping weight, and shipping volume of the inventory thus established. Tables C.5 and C.6 summarize the value and number of assets required in the inventory for the cases in this study.

SIMULATION

In this study, we have relied primarily on the latest version of Dyna-METRIC, Version 6.4. Originally developed by RAND in the early 1980s and well known to the Air Force, Dyna-METRIC is a capability-assessment model designed to explore ways to improve logistics support to weapon systems. Using information about planned flying programs, the characteristics of aircraft components, and response characteristics of logistics resources, Dyna-METRIC assesses the effects of operational dynamics, projects operational-performance measures (such as aircraft availability and sorties completed), and

[22]Our computation appears generally to underestimate the requirement computed by SBSS (compare "Modeled" to "Demand-Based" in Table A.7). We suspect it does so because a different order-and-ship time was used in AMC's calculations. We used 4 days for all parts in our calculations, based on inputs provided by AMC. In the actual calculations, however, it is likely that times longer than this standard would have been used, based on then-current experience at the FSLs. For example, Crimiel (1991) found that order-and-ship times seen by FSLs during Desert Shield averaged 18.4 days. Use of that time, for example, would have resulted in a higher requirement being computed.

identifies potential logistics problems. Dyna-METRIC has been used in many RAND and Air Force studies, and serves as a major component of the Air Force Weapon System Management Information System (WSMIS).

Version 6 of Dyna-METRIC is a discrete-event simulator that uses Monte Carlo sampling in lieu of the direct computations of probabilities found in earlier versions. The shift from a strictly analytic approach (which interprets the mathematics directly) to Monte Carlo sampling was made for two reasons. First, modeling of management adaptations in repair and distribution could not be addressed analytically. Second, some of the assumptions made to solve the mathematics underlying the analytic version limit the accuracy of the model's results (Isaacson and Boren, 1993).

Using Dyna-METRIC, we were able to measure aircraft status, sorties achieved, and supply-issue success rate for any given day. These measures mimic the measures used by the Air Force in assessing its own status. Thus, simulation results for a set of assumptions can be compared with Air Force experience under similar conditions.

In this section, we discuss several features of Dyna-METRIC that proved particularly important to the study. We also discuss an interesting and perhaps important anomaly that has been found in Dyna-METRIC's treatment of variability in demand rates.

Sortie Feedback

One little-known feature in Dyna-METRIC, Option 20, was found to be particularly important in this study.[23] In its "default" mode, Dyna-METRIC executes the planned sortie program each day, even if some sorties would be unachievable because of grounded aircraft. When aircraft availability is high (as it typically is for fighters and bombers, for example), this mode of operation provides a reasonable approximation. However, when aircraft availability is low (as it is for C-5 aircraft that are en route), this mode will tend to overstate part-

[23]Option 20: "Fly achievable sorties. Reduce the number of sorties flown to reflect the number of aircraft available at each base. If not used, component removals are generated as if the requested number of sorties were actually flown, regardless of whether aircraft were available to achieve that rate" (Isaacson and Boren, 1993, p. 71).

demand rates. Dyna-METRIC provides Option 20 to limit the sortie program for any day to only those sorties that could be achieved.

This option has two advantages. First, experienced demands are limited to those that would result from the sorties that could be flown on any day. Second, with this option selected, sorties that could not be flown on one day are deferred to the next day.[24] By limiting demands to those that could be achieved based on available aircraft, we are able to observe that inventory is often not as effective, over the long run, as might be expected. Although providing an additional item of inventory initially tends to raise aircraft availability, improved aircraft availability means that more sorties can be flown, which results in more parts failing. Over the long term, the effect of inventory on performance might be overstated if this "sortie feedback" were not taken into account.

Extensions to Dyna-METRIC

Four extensions to Dyna-METRIC have been implemented at RAND in support of this study (none of them is currently available in any formal release):

Report issue effectiveness. When this option is selected, Dyna-METRIC reports the number of supply requests that would have been honored (1) if only the assets on hand at the beginning of the day were considered, and (2) if all assets available throughout the day were considered. The actual issue effectiveness achievable should be somewhere in-between.

Report aircraft availability averaged over time. When this option is selected, Dyna-METRIC generates a database containing the number of aircraft available at the end of each day at each location on each trial. A simple post hoc calculation can then generate the average availability over time—a measure somewhat more congruent with

[24]This "rolling over" of sorties mimics the Air Force's own practices to some extent, but is limited to only one day. In addition, AMC reports that it frequently cancels sorties that could not be flown, rescheduling them for the next day but avoiding the "missed sortie." Because of this practice, the simulation reports a departure reliability that is lower than the Air Force would report under the same circumstances.

Air Force practice than considering only the availability on a particular day.

Schedule only whole sorties. When this option is selected, Dyna-METRIC will attempt to fly only an integer number of sorties on each day. Normally, Dyna-METRIC would fly fractional sorties if they were requested, which is very rarely the case in analyses involving fighter and bomber aircraft. In this study, however, it is not unusual for activity rates to be so low that fractional sorties are both the norm and significant. With this option, only integral sorties are flown each day (with any fraction remaining accumulated over time), creating a more realistic representation of actual Air Force experience.

Use deterministic "next-day" transportation times. Normally, transportation times in Dyna-METRIC are exponentially distributed, with a mean as specified in the user's inputs. For our purposes, this was appropriate most of the time—a transportation time of 2 days might be realized as 1 day on one simulation run and as 5 days on another simulation run. However, to model commercial express carriers, we needed to have some transportation actions that always took place in a specific amount of time (that is, "next day" delivery should always mean 1-day transportation). We added a new input marking to Dyna-METRIC that signified a deterministic transportation time (one that always occurs in the indicated time). This feature was used for modeling all CONUS commercial express transportation legs.

Measures of Merit

For comparing the standard infrastructure with a high-velocity infrastructure, we considered three measures of weapon-system performance: *aircraft availability, departure reliability,* and supply *issue effectiveness.*

For *aircraft availability,* we determined the fully mission capable (FMC+) rate from a simulation run in which we assumed that all reparable assets on the aircraft must be operational.[25] Partially

[25]As noted in Chapter Two, the fully mission capable rate reported by the simulation also includes those aircraft that would, in actual practice, be considered either par-

mission capable (PMCS) status was determined from a simulation run in which we assumed that only a restricted subset of those parts must be operational. Since AMC did not have a suitable list of such "essential" parts, we developed our own list by examining demand rates experienced at AMC locations (see Table C.11). Our list of essential parts consists of 87 line items that were demanded at the same rate (relative to level of operational activity) at all locations where we would expect demands. That is, we compared worldwide average demand rates to the demand rates actually experienced at individual bases; where these rates were very nearly the same, it suggested that demands for those parts were not being deferred from the en route system to the PSPs, that these were "essential" parts.

To develop a measure of *departure reliability*, we compared the number of sorties that were generated on a particular day with the number that were scheduled for that day. Dyna-METRIC will attempt to fly tomorrow any sorties that cannot be flown today, not unlike AMC's rescheduling of sorties in response to maintenance or supply problems. While such rescheduled events are sometimes not counted as missed sorties by the Air Force, they are always counted as missed sorties by Dyna-METRIC.

Issue effectiveness, a popular measure of supply-system performance, was originally considered as a measure of merit but proved to be problematic in this study. It is a measure of the supply system's ability to provide a needed part at the time a request is made. Due to the level of detail modeled in the simulation (accounting is only done at the end of each simulated day), Dyna-METRIC is not able to report the proportion of supply requests that are honored at the time they are made. What we were able to measure was the proportion of requests made on any day that would have been met that same day, assuming that either (1) only the assets on hand at the beginning of the day were available to meet the requests or (2) all the assets available at the end of the day could have been used to meet the requests. This seems to be a reasonable proxy for the measure used by the Air Force; their experience should be somewhere between those bounds.

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tially mission capable due to maintenance shortages or not mission capable due to maintenance shortages. Hence, we have used the label "FMC+" in this report.

However, it turns out that issue effectiveness makes a poor measure for comparing the standard infrastructure and high-velocity infrastructure (HVI), because an HVI, by its very nature, will favor speed over inventory. An HVI provides rapid transportation of needed parts from other locations (such as a PSP), which lessens the requirement to keep the part locally. Rapid transportation often allows more centrally located inventory to be utilized more effectively than locally held inventory. As a result, we would expect issue effectiveness under HVI to be lower when other measures are held constant (see footnote 18 in Chapter Two).

While issue effectiveness did not prove to be a good measure for comparing the current infrastructure with a high-velocity infrastructure, this study does not imply that issue effectiveness is an ineffective or inappropriate measure of supply-system health. Changes in issue effectiveness can signal changes in other measures of interest to the system, such as *not-mission-capable-due-to-maintenance* and *cannibalization* rates. For example, when the system is in relatively stable operation, decreases in issue effectiveness tend to indicate problems in the supply system and may presage increases in cannibalization (to make up for missed supply issues). In the future, the supply community will need to establish new standards for issue effectiveness commensurate with the HVI philosophy of trading inventory for speed.

Observations About the Variance-to-Mean Ratio

In Chapter Three ("Variability of Demand Rates Is Less Damaging"), we noted an anomaly in results concerning high variance-to-mean ratios (VTMRs). In the analysis shown there, we explored how the standard and high-velocity infrastructures respond to highly variable demand patterns. It was expected that performance would be degraded when demand patterns are more variable than have been planned for. Indeed, that is what we usually see. But for en route bases, we observe the apparently anomalous effect that performance appears to improve as variability increases.

The explanation lies in the way variation in demand rate is introduced into Dyna-METRIC—with the way VTMR is implemented. Most logistics models, including Dyna-METRIC, assume that the average rate of demands on the supply system is proportional to the

flying intensity and that the proportionality is constant over reasonable lengths of time. Variation around the mean demand rate is characterized by a factor called the *variance-to-mean ratio,* which is defined as follows:

$$\text{VTMR} = \frac{\text{(the variance of the number of demands per unit time)}}{\text{(the expected number of demands per time)}} \tag{A.1}$$

Variability in the rate at which demands arise is a naturally occurring phenomenon in logistics systems. From a computational standpoint, it would be convenient if we could assume that demands arise through simple Poisson processes (having a VTMR of 1), which are well understood and computationally tractable. However, years of observation have shown that the rate of arrival of demands on the Air Force supply system cannot be described that way; demands arise with less predictability than that. The *variation* in demand rate exceeds the *mean* of the demand rate for most parts. Some form of compound Poisson (usually the negative binomial) is usually used to describe these observations (see Crawford, 1988).

Air Force computations typically limit the VTMR to 5 (or ignore variance in demand processes altogether). However, observations of Air Force data suggest that VTMRs may actually range as high as 50.[26] Because the evidence is ambiguous about the source and magnitude of the VTMR, we have used a fixed VTMR of 1.5 for all parts in this study. That ratio was selected on the basis of observations by Crawford (1988) of C-5 parts in the late 1980s. To introduce greater variation in demands than anticipated, we increased the VTMR for all parts from 1.5 to 8.0.

The relationship between VTMR and performance is a complex one. At its heart is the fact that when more demands than expected occur, the system is at risk of not being able to replace a broken part in an aircraft with a serviceable one.

The "expected" number of demands (i.e., the mean number represented by the demand rate) seldom arises in practice. The VTMR

[26]See Crawford (1988), for example.

characterizes the extent to which demand rates that actually occur differ from the expected rate. Demands in excess of the expectation must be met with stock set aside to protect against such swings. When stocks in the system are not sufficient to cover an unexpected demand swing, performance of the fleet is reduced and aircraft may be grounded.

For a fixed amount of stock available, there are some circumstances under which the Air Force is at less risk of such a failure under high VTMR than it would be under low VTMR. To understand how this might be, let's look at a specific example. For this example we have used the part with the highest demand rate in our database of C-5 parts (simplified somewhat by assuming a NRTS rate of 100 percent as is the case for FSLs):

- FSC 4920
- NIIN 010347681
- NOUN DGL RO UNIT
- QPA 1
- OIMDR 0.06762 demands per landing
- NRTS 100% (actually 13%)
- OST 17 days

The requirement for stock (level) at a location depends on the above characteristics, the expected activity level at that location, and the amount of safety stock allowed for under the stockage policy in effect. In this example, we will vary the activity rate and the order-and-ship time (OST); as in all the calculations in this study, we assume a stockage policy that allows $(3 \times \text{pipeline contents})^{1/2}$ for safety stock. The *requirement* at a location is that stock necessary to protect the location from demands that are expected to occur between the time a part is removed from an aircraft and the time a replacement for that part can be acquired from the wholesale or retail logistics system (assuming that no stock is on the shelf at the location itself). That is, when the NRTS rate is 100 percent (no local repair is being undertaken), the requirement protects the location against demands that are expected to occur during the OST for the part.

Assuming an activity rate at our sample location of 0.5 landing per day, the number of demands we would expect during an OST of 1 day would be

$$\begin{aligned} 0.0338 = {} & 0.06762 \text{ demand/landing} \\ & \times 1 \text{ QPA} \\ & \times 0.5 \text{ landing/day} \\ & \times 1 \text{ day OST} \end{aligned} \qquad \text{(A.2)}$$

The corresponding safety level would be

$$0.3185 = (3 \times 0.0338)^{1/2} \qquad \text{(A.3)}$$

The requirement thus computed would be 0.0338 + 0.3185 rounded to the nearest integer quantity, or zero.[27] When the activity rate is very low, even a high-demand-rate part will tend to have a low requirement.

In execution, the "expected" demand rate seldom occurs. We represent the stochastic behavior of demand arrivals with the VTMR. A VTMR of 0 would lead to "expected" demand arrivals. A VTMR of 1 (i.e., the variance is equal to the mean) would lead to Poisson-distributed demand arrivals. Larger VTMRs lead to more-variable demand arrivals.

Figure A.5 shows the probability that a particular number of demands will be experienced given a mean (expected) demand rate of 5 and a VTMR of 1 (black bars) or a VTMR of 8 (gray bars). Because the negative binomial is used to model VTMRs of other than 1 (where the Poisson is used directly), higher VTMRs lead to distributions of demands that are more and more clustered—more demands are separated by short intervals with long gaps between clusters.[28]

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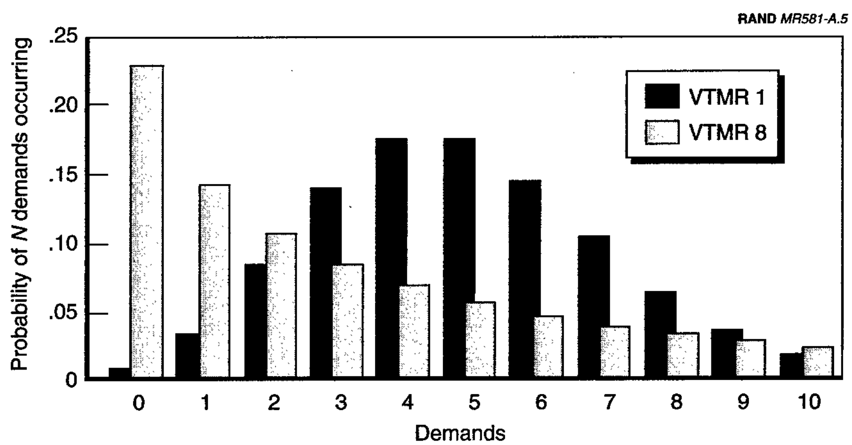
[27]Assets obviously come in integer amounts (0,1,2,..., n); various rounding rules are in effect under different stockage policies. Here, we have elected simply to round to the nearest integer.

[28]To compute the negative binomial, we used the following recursion:

$$f(0) = p^r$$

and

$$f(x+1) = \frac{r+x}{x+1}(1-p)\ f(x), \text{ for } x = 0, 1, 2, \ldots, n$$



NOTE: Assumes mean demand rate of 5.

Figure A.5—Demand Occurrences Under VTMR 1 and VTMR 8. The negative binomial is used to model VTMR greater than 1; therefore, as VTMR increases, it becomes more likely that no demands will be seen in a given time period.

Assuming a particular VTMR, we can calculate the probability that the requirement will be sufficient to cover the demands that will occur. For our example, the computed requirement (0) would be adequate 97.30 percent of the time under a VTMR of 1.5. That is, only 27 times out of 1,000 would we expect to need more than that amount of stock. But under a VTMR of 8, that level would be adequate 99 percent of the time. Because it is more often the case under a VTMR of 8 that no demands will be seen in a particular period of time, a stock level of 0 would pose less risk under a VTMR of 8 than under a VTMR of 1.5.

This phenomenon is illustrated in Figures A.6 and A.7. In Figure A.6, the pipeline size and resulting requirement are shown for our sample

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where $p = \frac{1}{\nu}$ and $r = \frac{\mu}{\nu - 1}$
for mean μ and VTMR $\nu > 1$. See Miller and Abell, 1992.

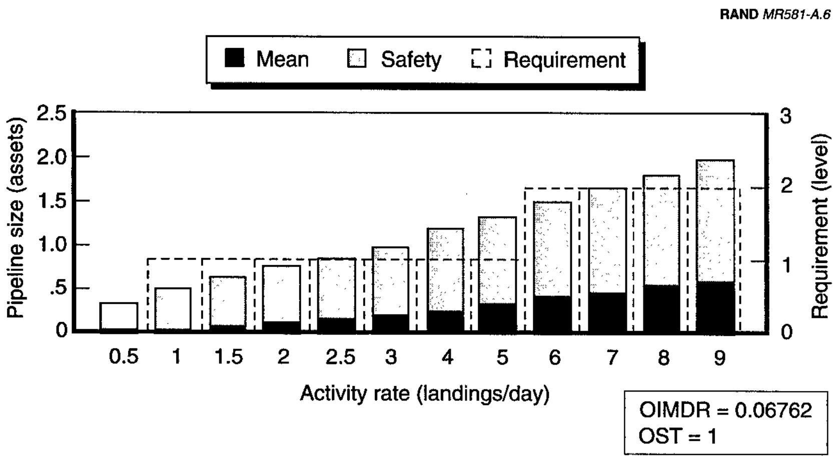

Figure A.6—Pipeline Size and Resulting Asset Requirement for Various Activity Rates. As activity rates increase, the amount of stock required to cover the order-and-ship time also increases; pipeline size is dominated by safety stock at this relatively short order-and-ship time.

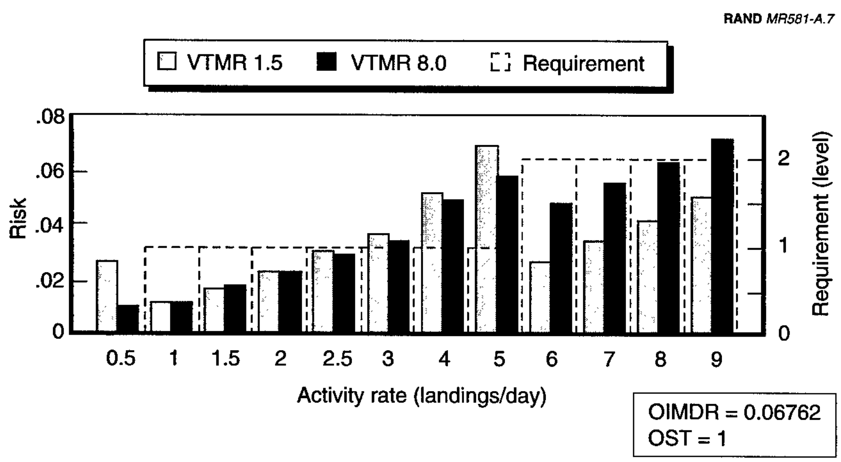

Figure A.7—Probability That the Requirement Would Not Be Adequate to Cover Demands for Various Activity Rates. At most activity rates below 6 landings per day, the computed stock level would produce better performance under a VTMR of 8 than under a VTMR of 1.5.

part for various activity rates. The dark portion of each bar shows the expected pipeline size (parts required to cover the OST); the gray portion of each bar shows the safety level. The dashed bars show the (rounded) requirement that results. In Figure A.7, the risk that a particular number of assets will not protect the location, given various activity rates, is presented for a VTMR of 1.5 and a VTMR of 8. Where the gray bar is taller than the dark bar (for example, at 3 landings per day), greater risk would be assumed under a VTMR of 1.5 than under a VTMR of 8, if assets are equal to the requirement allocated to the location.

This illustration is continued in Figure A.8, where the risk inherent in the requirements computation is presented across a range of order-and-ship times. Here, we have held the activity rate constant at 0.5 landing per day and have varied the OST. Under these conditions,

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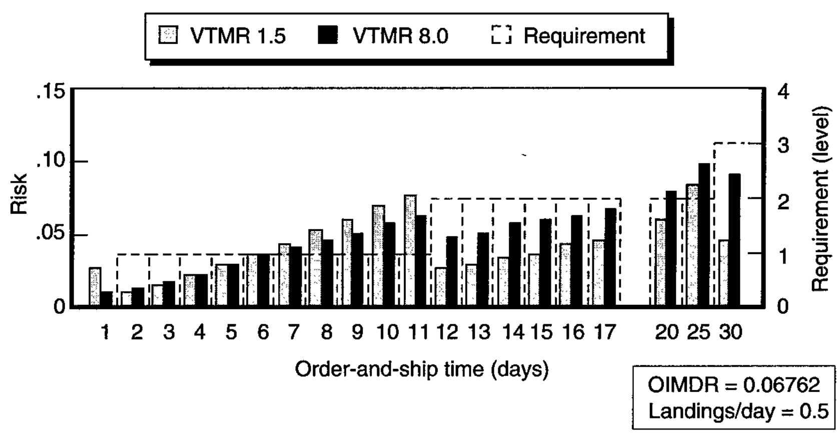

Figure A.8— Probability That the Requirement Would Not Be Adequate to Cover Demands for Various Order-and-Ship Times. With order-and-ship times less than 12 days, the computed stock level generally produces better performance under a VTMR of 8 than under a VTMR of 1.5.

OSTs of less than 12 days result in the same or less risk being assumed under a VTMR of 8 than under a VTMR of 1.5.[29]

Lower risk will tend to translate into better performance. Hence, when we compare the standard infrastructure (with its relatively long OST) to the high-velocity infrastructure (having a shorter OST) at en route locations (where both demand rates and activity rates tend to be lower than at CONUS main bases), performance under a VTMR of 8 tends to be better than performance under a VTMR of 1.5. The relatively small amount of stock available (the same amount in both cases) tends to present a lower risk of not covering demands under a VTMR of 8 than under a VTMR of 1.5.

Consequences

The practical consequences of this observation are, first and foremost, a warning to policymakers and analysts not to overlook the importance of often-ignored parameters. Estimates of resource requirement may be substantially optimistic or pessimistic as a result of uncertainties over which no control can be exercised. Beyond that, it must be noted that the effect observed here is a function of having chosen the negative binomial as a way of implementing VTMRs other than 1. While this is a common and convenient choice, there is debate about the underlying mechanism that produces the variation in demand rates observed in Air Force data.[30]

It is possible, for example, that the bulk of such variation is being generated by slow movement in the mean of an otherwise Poisson process. Because demand rates are relatively low, long observation times are typical in the measurement of these numbers (D041, for example, measures demands over 3-month periods). Variance in demand rates is, necessarily, measured over even longer times. Over such long periods, it seems plausible that the actual mean of the demand process has simply moved. If that interpretation were to predominate, the force of these observations would certainly be reduced.

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[29]The order-and-ship times and activity rates chosen in these examples are consistent with those modeled in this study; see Table A.3.

[30]See, for example, Adams et al., 1993, especially p. 22.

The clustering interpretation (for which the negative binomial *is* a good model) does have precedence in at least some cases, however. There are parts for which clustered removals are the norm. For example, fan blades from the first-stage fan of the TF-39 engine on the C-5 are typically replaced several at a time. As may be imagined, these fans must be balanced to within relatively fine tolerances. When one blade of a fan is damaged, it is usual for several other blades to be removed and replaced at the same time. These clustered removals would look, for all intents and purposes, just like a high VTMR. In such cases, the observations in this section would suggest that low-demand parts, under regimes having short OSTs, would perform better than we might otherwise expect.

Appendix B

TUNING THE LOGISTICS SYSTEM

Although we explored several approaches to improving en route performance in our simulation model, the fully-mission-capable and departure-reliability rates reported by the simulation for en route locations remain lower than would be acceptable in most parts of the Air Force. This may be, in large part, because the C-5 can conduct most of its mission in a partially mission capable (PMC) status. The simulation shows us that only a small fraction of aircraft en route are likely to be in fully mission-capable condition. Further, the simulation appears to be systematically pessimistic in its report of mission-capable status and departure reliability. Air Mobility Command's reports of departure reliability tend to be more optimistic than the simulation, perhaps because of AMC's practice of cancelling, then rescheduling, sorties that the simulation would see as missed departures.

Those differences notwithstanding, we would like to know whether performance of the C-5, especially en route, can be improved. To better understand how performance in the en route portion of the system might be improved, we considered several excursions from the assumptions used in this study. While not directly related to the question of how a high-velocity infrastructure (HVI) would work, these results may be helpful in seeking further improvements to C-5 performance. The following approaches were explored:

- Additional PSPs
- Fewer PSPs
- Greater range of items in stock

- Different beddown assumptions.

We discuss each approach in turn.

ADDITIONAL PSPs MIGHT IMPROVE PERFORMANCE

Discussions with AMC, U.S. Transportation Command (USTRANSCOM), and Defense Logistics Agency (DLA) personnel suggested that transportation legs between primary supply points (PSPs) and the forward supply locations (FSLs) they serve cannot be significantly improved beyond what we posit in this study. Since a large fraction of parts are repaired at the PSPs, it might be reasonable to consider creating new PSPs located so as to serve the FSLs better.

In this section, we posit the creation of two such PSPs, one in Europe and one in Asia. We did not consider the political ramifications of increased American presence on foreign soil, nor did we consider the additional costs of constructing and operating such facilities, although those might be critical considerations. In any case, it may be possible to collocate such new facilities with existing major support facilities in Europe and Asia, taking advantage of existing political arrangements and existing capital investments.

The new PSPs in our analysis would provide both supply and repair service (as the current PSPs do now). They would have a physical proximity to the FSLs they serve, ensuring rapid delivery for most parts. They would also deal directly with wholesale sources of repair, shipping directly to and from wholesale sites.

For the standard infrastructure, movements between FSLs and their PSPs were reduced to 6 days retrograde and 3 days forward. Movements to and from the depot remained at 17 days. For the high-velocity infrastructure, movements between FSLs and their PSPs were set at 1 day each way, as were movements between the new PSPs and the depot. As opposed to the fixed (deterministic) "next-day" times used for CONUS PSPs under the high-velocity infrastructure in the main body of this study, these movement times were distributed exponentially with a mean of 1 day. This means that, while the average movement time for assets along these segments was 1 day, a significant proportion of the movements actually took longer than that. Our intent in permitting these transportation

times to vary was to reflect some of the uncertainty inherent in dealing with shipments overseas.

In creating our new PSPs, we reduced the workload at the existing PSPs (Dover AFB and Travis AFB); they continued to support their own and other Western Hemisphere activities (IDOV and ISUU in the model), but no longer supported the FSLs. Forward supply locations in the Pacific (coded with an initial letter "P" or "R" in the model) were assigned to a new PSP located somewhere in their vicinity (coded "JPAC" in the model). The remaining FSLs (coded with an initial letter of "E," "H," or "L" in the model) were assigned to a new PSP located in Europe (coded "JLNT" in the model).

Implementing European and Asian PSPs would reduce inventory requirements for an HVI by a small amount and would improve performance slightly, as shown in Table B.1.[1] As shown in Figure B.1, en route performance would be improved under an HVI. Mission-

Table B.1

Change in Performance Measures and Inventory If New PSPs Were to Be Introduced

	Mission-Capable Status (percentage point)		Departure Reliability (percentage point)		Inventory Value ($K)		
	Standard	High Velocity	Standard	High Velocity	Standard	High Velocity	
CONUS Main	+1.0	+0.2	0.0	0.0	+905	+782	
Guard & Reserve	–1.0	–0.2	0.0	0.0	0	0	
En Route	–4.2	+5.5	–7.0	+7.1	–1,945	–3,518	
Total	–0.9	+1.2	–4.2	+4.3	–1,040	–2,736	Bases
					+10,484	–761	Shops
					+7,964	+2,630	Depot
					+17,409	–868	Total

[1]The inventory requirement at CONUS main bases increases slightly because of an error inadvertently introduced into the flying program at Altus AFB. That error affects the inventory figures ($709K for 9 additional assets) but has little effect on overall performance and no effect on the conclusions reached here.

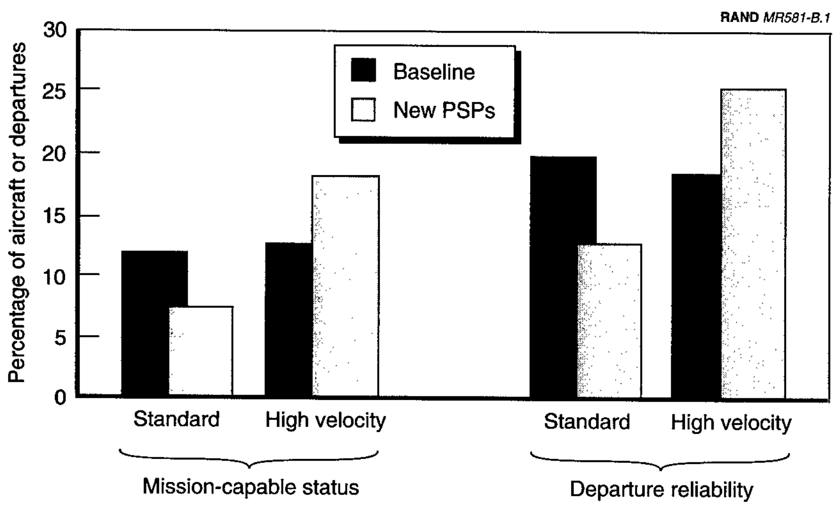

Figure B.1—En Route Performance With and Without PSPs in Europe and Asia. New PSPs would improve performance under a high-velocity infrastructure, but not under the current infrastructure.

capable status would be just over 5 percentage points better, and departure reliability would improve over 7 percentage points—roughly 2 additional fully mission-capable sorties per day.

New PSPs would not be beneficial under the current infrastructure. The volume of aircraft activity being supported by the Dover AFB and Travis AFB PSPs (JDOV and JSUU in the model) was split between those locations and the two new PSPs. Hence, the volume of activity supported by the current PSPs was substantially reduced.

As a result, the amount of inventory allocated to each PSP in our requirements computation was reduced somewhat. Each PSP now supports a smaller base of activity and so requires a smaller inventory. Even though the total inventory requirement across PSPs increases somewhat, the ability of each PSP to cover demands is reduced slightly. More parts see too low a projected demand rate to qualify for inclusion in the requirements computation at the (new) smaller PSPs than at the (former) larger PSPs.

For the standard infrastructure, that reduction in available inventory translates into a drop-off in performance. For the high-velocity infrastructure, the reduction in available inventory is compensated for by the higher speed with which stock outages are corrected: Performance improves.

MORE-CENTRALIZED SUPPORT WOULD NOT IMPROVE PERFORMANCE

Centralization of intermediate support activities (i.e., PSPs) might lead to simpler lines of communication, simpler management, and reduced resource requirements. Would it also improve performance? Here, we posit a single PSP, at which we locate all inventory assets except those protecting flight-line maintenance and those needed to support depot repair. All intermediate repair is also located at this centralized intermediate support facility. (Slight improvements in movement times could be achieved by locating such a facility at an express carrier's major hub.)

Such a consolidation would have little, if any, effect on overall performance. Under an HVI, fleetwide mission-capable status would be about 1 percentage point worse, whereas departure reliability would improve almost 4 percentage points, as shown in Table B.2. The

Table B.2

Change in Performance Measures and Inventory If PSPs Were to Be Centralized

	Mission-Capable Status (percentage point)		Departure Reliability (percentage point)		Inventory Value ($K)		
	Standard	High Velocity	Standard	High Velocity	Standard	High Velocity	
CONUS Main	+0.4	–3.4	0.0	0.0	+14,870	+6,374	
Guard & Reserve	+4.1	–1.9	0.0	0.0	+2,210	+550	
En Route	–1.3	+4.6	–2.5	+6.1	0	0	
Total	+1.3	–1.1	–1.5	+3.7	+17,080	+6,924	Bases
					+47,557	–132	Shops
					–58,779	–7,715	Depot
					+5,859	–922	Total

effect on en route performance of having a single PSP, shown in Figure B.2, is that mission-capable status and departure reliability would both improve under an HVI (4 and 6 percentage points). Almost no difference in inventory requirement would result in the high-velocity case (smaller by less than $1 million). An increase in inventory requirement would result in the standard infrastructure case.

Under the standard infrastructure, such centralization would be slightly beneficial to performance, improving FMC+ rates fleetwide by over 1 percentage point but reducing departure reliability by about 1.5 percentage points. We have assumed that transportation from main bases to the centralized support facility would take 4 days for retrograde and 2 days for forward movement. While actual times might be shorter, the result of our assumption is that main-base flight lines are 2–4 days farther away from their main source of repair and supply than they were when they provided their own intermediate-level support. Even with a slight increase in inventory (roughly $6 million), the effect on performance is mixed and small.

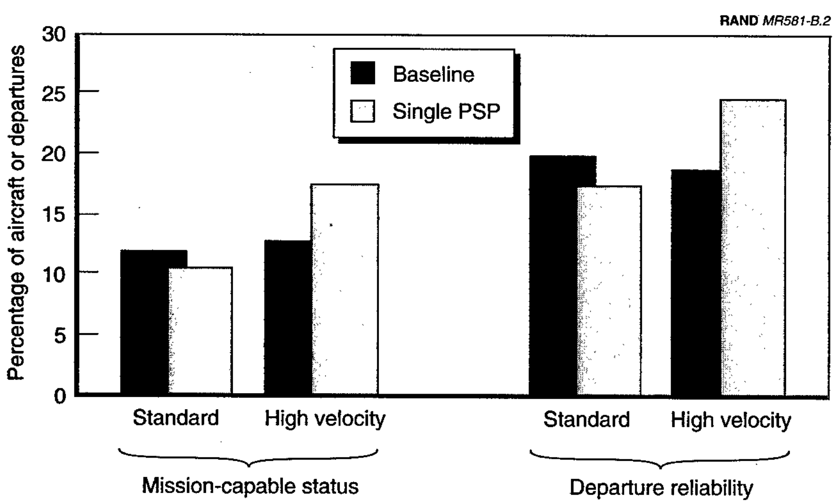

Figure B.2—En Route Performance If PSP Functions Were to Be Consolidated. Centralizing PSP functions appears to have benefit only for the HVI.

INCREASING THE RANGE OF PARTS WOULD NOT BE EFFECTIVE

Of the 1,908 modeled line items on the aircraft, our requirements computation for the high-velocity case is able to justify levels for fewer than 1,000 parts. Almost half the range of line items is excluded from the requirement because the probability of seeing a demand is simply too low to justify holding an asset in the pipeline inventory. Table C.6 illustrates the inventory requirement we computed for key cases in this study. The last column in that table shows the range of items—the number of distinct line items—contained in the requirement.

In reality, those demands of such low probability that we cannot justify having an asset to cover them *do* happen sometimes, and the logistics system must service them when they happen. When there is no stock in the inventory to cover a demand for one of these parts, the aircraft from which that part is taken will be grounded until the removed asset can be repaired. In the standard infrastructure, the average wait for that part would be 96 days; in the high-velocity infrastructure, that delay would be only around 13 days on average.[2] In practice, such rare events are usually handled by priority movement and repair: *In practice,* the standard and high-velocity infrastructures would probably behave much the same.

In this section, we consider two ways of providing inventory to shorten that delay. In the first approach, we make sure that the wholesale system has at least one asset for each part in the inventory. In the second approach, we make sure that each FSL has at least one asset for each LRU in the inventory.

Rounding Out Wholesale Inventory

We might expect to be able to improve overall performance by including in the inventory an asset for each of those parts that would otherwise not qualify. That way, when one of the low-probability

[2]These times are longer than the 67-day and 8-day average turnaround times cited in Chapter Two for the standard and high-velocity infrastructures, respectively, because, in this case, we assume that repair of *these* parts could be undertaken only at the depot.

events did occur, we would have an asset on the shelf to ship to the grounded aircraft, and could replace it with the eventually repaired asset removed from the grounded aircraft. For this excursion, we ensured that one asset of each type was available at the depot; that asset could then be applied against a demand anywhere in the world.

Such an approach would increase the value of computed inventory under both infrastructures, as shown in Table B.3. The value of inventory under the standard infrastructure would rise by over $6 million, while the value of inventory under the HVI would rise by $9.5 million.

The effect on performance would be fairly modest. Fleetwide, FMC+ rates were seen to fall almost 2 percentage points under the standard infrastructure and rise 1.4 percentage points under the HVI. The effect on departures would be slightly more pronounced.

As shown in Figure B.3, en route locations would see a more pronounced effect from this increased inventory. The HVI would benefit by over 5 percentage points in FMC and over 11 percentage points in departures. The standard infrastructure would suffer nearly the

Table B.3

Change in Performance Measures and Inventory If All Parts Were to Appear in the Owned Inventory

	Mission-Capable Status (percentage point)		Departure Reliability (percentage point)		Inventory Value ($K)		
	Standard	High Velocity	Standard	High Velocity	Standard	High Velocity	
CONUS Main	−1.0	+0.6	0.0	0.0	0	0	
Guard & Reserve	−0.8	−0.2	0.0	0.0	0	0	
En Route	−5.0	+5.4	−7.6	+11.2	0	0	
Total	−1.9	+1.4	−4.5	+6.7	0	0	Bases
					0	0	Shops
					+6,359	+9,533	Depot
					+6,359	+9,533	Total

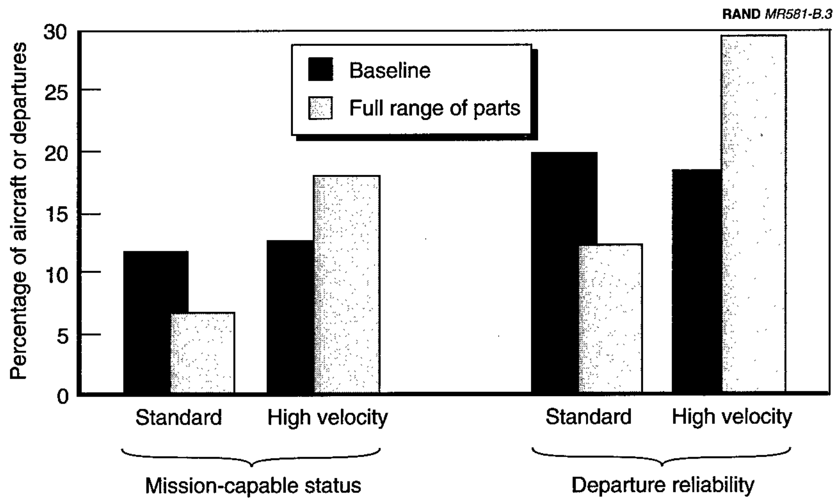

Figure B.3—En Route Performance If the Inventory Were to Contain the Full Range of Parts. Forcing the system to have at least one of each part in inventory would be effective only for the HVI.

same amount of *decline*, although this decline may well be an artifact of the simulation.[3]

Making FSL Stocks More Robust

Another approach to increasing performance by increasing the range of parts held in the inventory would be to ensure that each of the FSLs has at least one of each part for which it might find a need. Ensuring that there is at least one of each line-replaceable unit (LRU)

[3]We are unable to demonstrate any particular reason for the decline in performance under the standard infrastructure. However, a detailed examination of simulation results leads us to speculate that our simulation of the standard infrastructure had not come fully to steady-state operation after the year simulated here. If the added parts have the effect of bringing the simulation more quickly to (or near) steady state, the unaugmented case (that is, the baseline case) might appear to have higher, but still falling, performance than the augmented case. This phenomenon would not be a problem with the HVI cases, since we believe that the HVI comes to steady-state operation much earlier in the simulation.

at each FSL might be expected to improve en route performance, and thereby to improve overall performance. Because there is no repair capability at FSLs, we need not provide them with any shop-replaceable units (SRUs), which are sub-units found within LRUs and are replaced only at repair facilities.

Our simulation of this approach led to an increase in the value of computed inventory of almost $300 million in both infrastructures. Under the HVI, that increase would nearly triple the required inventory. Table B.4 shows that the effect on performance fleetwide is quite modest. The effect on en route locations would be more pronounced, as shown in Figure B.4.

Taken together, these results suggest that adding to the range of parts, either on a fleetwide basis or just at the FSLs, would be effective only for the HVI, but appears to be an expensive way to improve performance.

CHANGING THE ASSUMED BEDDOWN CHANGES THE RESULTS

Air Mobility Command did not have available the average number of aircraft operating in each region. To compute the beddown of air-

Table B.4

Change in Performance Measures and Inventory If Each FSL Had at Least One of Each LRU

	Mission-Capable Status (percentage point)		Departure Reliability (percentage point)		Inventory Value ($K)		
	Standard	High Velocity	Standard	High Velocity	Standard	High Velocity	
CONUS							
Main	–0.2	+1.2	0.0	0.0	0	0	
Guard & Reserve	–1.3	+0.3	0.0	0.0	0	0	
En Route	–2.5	+5.8	–5.5	+8.3	+284,643	+289,129	
Total	–1.1	+1.9	–3.3	+5.0	+284,643	+289,129	Bases
					0	0	Shops
					0	0	Depot
					+284,643	+289,129	Total

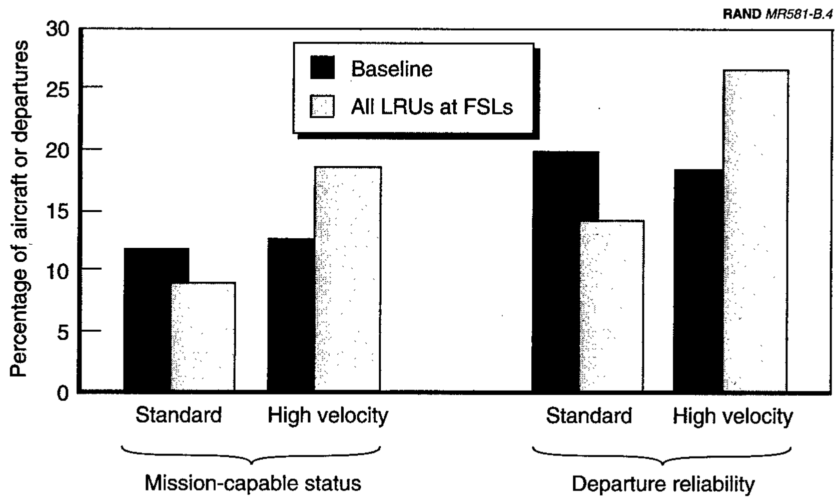

Figure B.4—En Route Performance If Each FSL Were to Be Provided the Full Range of LRUs. A performance advantage to giving all FSLs the full range of LRUs is seen only for the HVI.

craft, we developed a simple model based on assumptions about the proportion of aircraft entering a region that have to stand down (e.g., for crew rest), the average number of days an aircraft stays in a region, and the average number of locations visited by an aircraft on each day. With these factors and the number of landings to be accumulated in a region, the model determines the number of aircraft that should be in each region and the average flying programs for those aircraft. The various beddowns used in this study are shown in Appendix C.

The beddown we computed may place too few aircraft in each region. The presence of more aircraft in each region would decrease the amount of work undertaken on each of those aircraft and might increase en route performance.

To see what effect changing our assumed beddown would have on performance, we increased the number of aircraft supported by each FSL by 1. As shown in Figure B.5, having more aircraft at those loca-

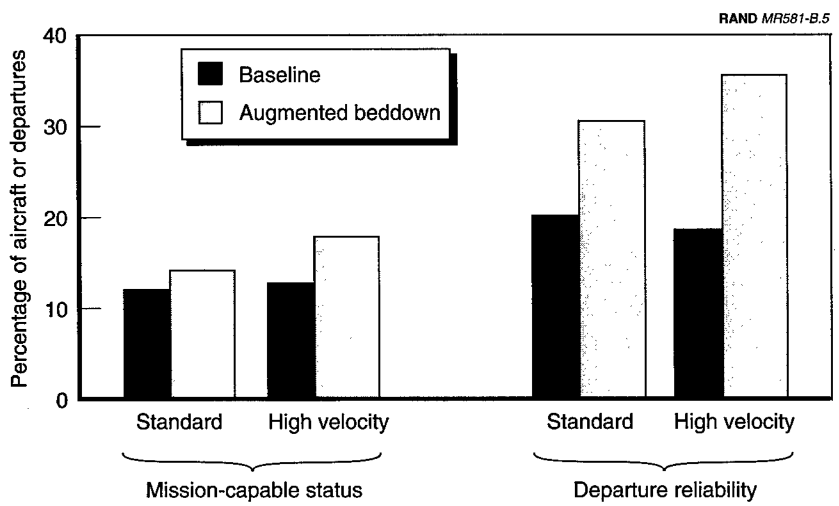

Figure B.5—En Route Performance If Beddown Assumptions Were to Be Changed. Providing more aircraft en route (taken from untasked aircraft at home stations) would improve en route performance.

tions tends to increase the mission-capable rates seen there. But there is an offsetting cost in mission-capable rate at the CONUS bases, as shown in Table B.5. Why? To get more aircraft in the en route system, we take "untasked" aircraft away from the CONUS bases, where they had been serving as a pool of available spares. It turns out that those untasked aircraft have a greater supply value at

Table B.5

Change in Performance Measures If One Additional Aircraft Were to Be Placed in Each Forward Region

	Mission-Capable Status (percentage point)		Departure Reliability (percentage point)	
	Standard	High Velocity	Standard	High Velocity
CONUS Main	–4.0	–3.8	0.0	0.0
Guard & Reserve	–3.8	–0.7	0.0	0.0
En Route	+2.5	+5.1	+10.9	+17.2
Fleetwide	–10.9	–9.1	+6.3	+10.1

the CONUS bases, where cannibalization is allowed, than they do at the en route bases, where cannibalization is not possible.

The particular change in beddown considered here is draconian. Each FSL was provided an additional aircraft, for a total of 11 aircraft removed from CONUS bases and added to the en route system. A smaller change might produce an overall increase in mission-capable rate, but would be beyond our current modeling capability.

Appendix C

TABLES OF RESULTS

This appendix contains tables of results from some key cases used in this study. The results shown are, in fact, summaries drawn from more-detailed simulation results. Performance and issue-effectiveness figures were collected under each case for each of 20 bases, 6 intermediate support locations (CIRFs), and 1 depot. Results were often collected on several simulation days. Except where noted in Table C.1, reported results are always for day 360 (that is, after one year of simulated operation). Each case involved simulation of 10 independent trials; the results shown here are the averages across those 10 trials.

The following tables are provided:

- Description of cases
- Beddown and program for selected cases
- Historical experience of AMC and AETC for 1993
- Sample detailed results
- Value of inventory for selected cases
- Number of assets in inventory for selected cases
- Mission-capable (FMC+) status for selected cases
- Departure reliability (FMC+) for selected cases
- Pessimistic issue effectiveness for selected cases

- Optimistic issue effectiveness for selected cases
- Parts thought to be "essential."

Table C.1 presents the names of the cases as shown in subsequent tables in this appendix, along with a brief description of each case. The starting point for the analyses in this study was a model of operation and support of the C-5 Galaxy during normal, peacetime operations under the current infrastructure—referred to throughout this report as the *standard infrastructure* model. In general, the analyses in this study involved side-by-side comparisons of that standard infrastructure with a *high-velocity infrastructure* under the baseline case and some excursion from that baseline case.

We approximated the flying of C-5 aircraft in each forward supply system (FSS) service region (and in the Western Hemisphere) with aircraft that flew out of fixed locations representing those regions. An early task was to determine how many aircraft, flying what program, would be necessary to approximate the Air Force's flying experience. Such data were not available, so we developed a computer program that, given some assumptions about typical mission profiles and the total number of landings to be accumulated in each region, developed an aircraft beddown and flying program. Table C.2 summarizes the three flying programs used in this study. The "Baseline" beddown approximates the Air Force's peacetime experience. The "Surge" beddown shifts aircraft and flying programs to support a low-intensity contingency. The "Major Operation" beddown reallocates aircraft in support of a Desert Shield–class contingency in the Pacific.

The performance experience of Air Mobility Command (AMC) and Air Education and Training Command (AETC) for the 12 months from April 1992 through May 1993 is summarized in Table C.3. The values in this table are taken from *Monthly Summary* (AMC, 1993), which indicates the number of aircraft that are mission capable (either PMC or FMC) and the number of aircraft that are in each of the PMC and NMC categories. That report presents no separate figures for the number of FMC aircraft; we derived the figures shown in that column of the table.

Table C.4 shows a combined summary report from two runs of the Dyna-METRIC simulation. The first run assumed that all parts in the

inventory appeared on each aircraft. It yielded results for the "FMC+," "Departure Reliability," and "Issue Effectiveness" columns in this table. The second run assumed that only the minimum-essential-subsystem parts appeared on each aircraft. It yielded results for the "PMCS" column in the table. *"Planned sorties"* are sorties per day. *"Mission-capable status"* is the percentage of the aircraft at each location found to be in the indicated condition (averaged over 10 trials).

The value of the inventory available to the simulation for selected cases is shown in Table C.5. In the "1992 Assets" and "Baseline (1992) Allocated in 1994" cases, these values represent the allocations of assets made by us—from the Air Force inventory (D041) in the former case and from an idealized inventory "purchased" on the basis of our requirements computation for 1992 in the latter case. Other cases in the table assume that the requirement computed for them was fully purchased.

The number of assets available to the simulation for selected cases is shown in Table C.6. In the "1992 Assets" and "Baseline (1992) Allocated in 1994" cases, these numbers represent the allocation of assets made by us—from the Air Force inventory (D041) in the former case and from an idealized inventory "purchased" on the basis of our requirements computation for 1992 in the latter case. Other cases in the table assume that the requirement computed for that case was fully purchased. In the final column, the "Range" shows the number of unique line items present in the inventory for that case. A maximum of 1,908 unique line items could appear in the inventory for any case.

The mission-capable status (FMC+ condition) reported by our simulations for key cases in this study is shown in Table C.7. The departure reliability for FMC+ aircraft reported by our simulations for key cases is shown in Table C.8.

Dyna-METRIC is able to show only the proportion of supply issues that would have been made (1) if only those assets on hand at the beginning of the day were available (*pessimistic*) and (2) if all assets arriving or repaired during the day were available (*optimistic*). The issue effectiveness reported by our simulations for key cases is shown in Tables C.9—pessimistic—and C.10—optimistic.

Table C.11 lists the parts declared in this study to be "essential." These parts were used to establish the PMC rate (capable of performing some but not all missions); for that purpose, the simulation assumed that only these parts needed to be operational. Parts were selected for this list by comparing the number of demands indicated in Standard Base Supply System (SBSS) data with the number of demands implied by data from the D041 system. Each of these parts had a recorded demand history, and there was little if any difference between the number of demands experienced within the FSS and the number of demands that D041 demand-rate data would have led us to expect within the FSS. That is, there was no evidence in the data we reviewed that demands for any of these parts were being deferred from FSLs to their PSPs. Data in the table come directly from D041, without interpretation.

Table C.1

Description of Cases

Case	Description
Baseline	Normal peacetime operations. Over 18,000 landings scheduled worldwide. Part characteristics were drawn from the 1992 D041 database; all parts had a demand-rate VTMR of 1.5. Stock was allocated to all locations on a basis similar to that used in the SBSS, using simulated prior-year history, and assuming requirements are fully funded.
Experienced Factors	Peacetime operation as if inventory were shaped in a different year from execution. A stock position was calculated as in the baseline on the basis of the 1992 D041 database. Those assets were then collected into a worldwide pool, which was allocated to all locations on the basis of the SBSS-like requirements computation, using factors from the 1994 D041. Unallocated assets were removed from the simulation.
High VTMR	Peacetime operation with highly variable demand rates. Baseline case with the demand-rate VTMR for all parts set to 8.0.
Surge	Peacetime operation plus support of a low-intensity contingency. The baseline case served as a basis for this case. After 360 simulated days of baseline operation, the flying load imposed by support to operations in Somalia was replicated in the Pacific. No adjustments in overall stock levels or allocation were made. Performance was sampled on day 390.
Major Operation	Support to wartime operations (one conflict). After 360 simulated days of baseline operation, the flying load seen during Operation Desert Shield was implemented in the Pacific. Most aircraft were activated, and training missions at Dover AFB and Travis AFB were curtailed. No adjustments in overall stock levels or allocations were made. Performance was sampled on day 390.
Transport Cutoff	Peacetime operation if CONUS transportation were to be cut off. After 360 simulated days of baseline operation, transportation legs between the depot and the CIRFs were cut off for 15 days. On simulation day 375, normal transportation was restored. Performance was sampled on day 360 and every day thereafter until day 390.

Table C.1—continued

Case	Description
FSS Assets Withdrawn	Peacetime operation if FSS assets were to be repositioned to PSPs. The baseline case served as the basis for this case, except that levels (and stocks) allocated to the FSLs were reallocated to their PSPs. Performance was sampled on day 360.
1992 Assets	Peacetime operation using owned assets. The baseline case with primary operating stock (POS) assets (as indicated in the 1992 D041) allocated to locations according to the requirement computed in the baseline case.
Random Distribution	Peacetime operation assuming no priority distribution. Distribution of serviceable assets from warehouses or the depot was to a randomly selected requester (rather than to the requester for whom the part would have the greatest value).
New Beddown	Peacetime operation assuming a different beddown of aircraft. Each region (FSL) was given one additional aircraft, taken from the pool of aircraft at Dover and Travis.
No Improvement	Peacetime operation assuming inventory were to be drawn down but none of the assumed pipeline improvements were to occur.
No Repair Improvement	Peacetime operation assuming inventory were to be drawn down but the only improvements that occurred were to be transportation times.
1/4 Repair Improvement	Peacetime operation assuming inventory were to be drawn down but only transportation and one-quarter of the assumed repair-time improvements were to occur.
1/2 Repair Improvement	Peacetime operation assuming inventory were to be drawn down but only transportation and one-half of the assumed repair-time improvements were to occur.
New PSPs	Peacetime operation assuming FSLs in Europe were to be served by a new PSP in Europe, and FSLs in Asia and the Pacific were to be served by a new PSP in Asia.
Single PSP	Peacetime operation assuming that all PSP and backshop functions were to be consolidated at a single, centralized support facility.
Full Range of Parts	Peacetime operation assuming that at least one of each part were to be present somewhere in the pipeline inventory.
All LRUs at FSLs	Peacetime operation assuming that at least one of each LRU were to be present in the inventory at each FSL.

Table C.2

Beddown and Program for Selected Cases

Base	Baseline		Surge		Major Operation	
	Aircraft	Sorties/ Aircraft/ Day	Aircraft	Sorties/ Aircraft/ Day	Aircraft[a]	Sorties/ Aircraft/ Day
EDAF	3	1.47	3	1.47	3	1.47
EDAR	1	1.28	1	1.28	1	1.28
EGUN	1	0.73	1	0.73	1	0.73
HECW	2	1.01	2	1.01	2	1.01
IDOV	5	1.61	4	2.01	6	1.86
ISUU	4	1.51	3	2.47	7	1.74
KCEF	13	0.07	13	0.07	3	0.63
KDOV	23	0.38	21	0.41	9	0.87
KLTS	8	0.38	8	0.38	8	0.38
KSKF	18	0.07	18	0.07	6	0.55
KSUU	17	0.38	18	0.40	7	0.88
KSWF	6	0.06	6	0.06	3	0.46
LETO	1	1.55	1	1.55	1	1.55
LPLA	1	0.63	1	0.63	1	0.63
LTAG	1	0.30	1	0.30	1	0.30
PAED	1	1.13	1	1.13	14	1.02
PGUA	1	0.61	1	0.61	7	1.03
PHIK	1	2.01	2	1.69	14	1.08
RJTY	1	1.56	1	1.56	6	1.18
RODN	1	1.25	3	1.10	11	1.11
TOTAL	109		109		111	

[a]Two aircraft have been "moved" from depot-maintenance status to the active fleet for this scenario.

Table C.3

Historical Experience of AMC and AETC for 1993 (percentage of possessed aircraft, scheduled departures, or supply requests)

Month	FMC[a] (%)	PMCM (%)	PMCS (%)	NMCM (%)	NMCS (%)	Departure Reliability[b] (%)	Issue Effectiveness (%)
APR	36.0	14.2	24.3	16.6	13.7	90.7	80.6
MAY	36.6	19.9	21.2	13.2	13.2	91.6	79.8
JUN	44.4	16.4	15.5	15.3	13.4	88.5	74.9
JUL	38.5	16.0	21.1	14.3	12.5	90.2	76.5
AUG	28.9	20.8	21.4	18.1	16.4	82.3	75.1
SEP	29.3	23.7	18.5	18.6	15.3	84.5	78.5
OCT	38.7	18.3	18.4	17.4	12.0	85.2	75.4
NOV	40.1	14.8	17.9	15.4	16.6	84.5	75.9
DEC	29.6	28.1	17.2	14.0	15.4	83.0	73.4
JAN	11.6	41.5	23.6	14.0	13.0	85.7	75.6
FEB	36.4	21.6	15.5	17.0	13.8	84.8	79.0
MAR	33.5	18.7	16.3	19.7	15.7	90.9	80.4

SOURCE: AMC, *Monthly Summary*, March 1993.

[a]Derived values.

[b]Includes home-based and en route departures.

Table C.4

Sample Detailed Results (baseline case, standard infrastructure: status on day 360, averaged over 10 trials)

			Mission-Capable Status (%)			Departure Reliability	Issue Effectiveness (FMC+) ((%)	
		Planned Sorties				(FMC+)		
Location	Aircraft	(per day)	FMC+	PMCS	NMCS	(%)	Minimum	Maximum
DEPO							94.5	95.1
JCEF							53.9	55.3
JDOV							77.3	82.2
JLTS							45.9	50.2
JSKF							33.9	40.1
JSUU							64.2	70.0
JSWF							11.9	22.0
EDAF	3	4.4	20.0	16.7	63.3	40.8	25.0	25.0
EDAR	1	1.3	0.0	40.0	60.0	0.0	0.0	0.0
EGUN	1	0.7	0.0	50.0	50.0	0.0	0.0	0.0
HECW	2	2.0	20.0	5.0	75.0	40.1	0.0	20.0
IDOV	5	8.1	12.0	20.0	68.0	22.4	0.0	15.0
ISUU	4	6.0	15.0	15.0	70.0	29.8	0.0	12.5
KCEF	13	0.9	80.8	11.5	7.7	100.0	16.1	50.0
KDOV	23	8.7	86.5	7.4	6.1	100.0	16.8	70.6
KLTS	8	3.0	68.8	15.0	16.2	100.0	12.3	51.9
KSKF	18	1.3	83.9	11.1	5.0	100.0	14.4	45.6
KSUU	17	6.5	83.5	7.7	7.7	100.0	32.2	66.3
KSWF	6	0.4	65.0	26.7	8.3	100.0	16.7	38.9
LETO	1	1.6	10.0	0.0	90.0	10.3	0.0	11.1
LPLA	1	0.6	10.0	60.0	30.0	9.5	0.0	0.0
LTAG	1	0.3	10.0	40.0	50.0	10.0	0.0	14.3
PAED	1	1.1	20.0	0.0	80.0	20.4	0.0	0.0
PGUA	1	0.6	10.0	70.0	20.0	9.8	0.0	0.0
PHIK	1	2.0	10.0	10.0	80.0	10.0	0.0	0.0
RJTY	1	1.6	20.0	0.0	90.0	19.9	0.0	0.0
RODN	1	1.2	0.0	10.0	90.0	0.0	0.0	20.0
En Route	24	31.6	12.9	20.4	66.7	23.0		
CONUS	85	20.8	81.3	10.9	7.8	100.0		
Fleet	109	52.3	66.2	13.1	20.7	53.6	18.3	57.6

Table C.5

Value of Inventory for Selected Cases ($thousands)

		Inventory Value ($K)				
Case	Infrastructure	Depot	PSPs	Bases	Total[a]	Note
Baseline	Standard	298,808	163,577	18,138	480,523	
	High Velocity	98,458	42,263	12,955	153,677	
1992	Standard	162,674	116,668	16,643	295,985	(b)
Assets	High Velocity	83,665	32,467	12,163	128,295	(c)
New PSPs	Standard	306,772	174,061	17,098	497,932	
	High Velocity	101,088	41,502	10,219	152,809	
Single PSP	Standard	240,029	211,134	35,218	486,382	
	High Velocity	90,743	42,131	19,879	152,755	
Full Range	Standard	305,167	163,577	18,138	486,882	
of Parts	High Velocity	107,987	42,263	12,955	163,206	
All LRUs at	Standard	298,808	163,577	302,781	765,166	
FSLs	High Velocity	98,458	42,263	302,084	442,806	
1994	Standard	267,933	170,700	22,199	460,833	
Requirement	High Velocity	118,897	31,137	14,661	164,696	
Baseline (1992)	Standard	145,205	128,021	20,794	294,020	(d)
Allocated in 1994	High Velocity	71,711	24,041	13,038	108,790	(e)

[a]Totals have been rounded.

[b]$614,959,000 unallocated; $184,538,000 unmet.

[c]$782,649,000 unallocated; $25,382,000 unmet.

[d]$186,502,000 unallocated; $166,812,000 unmet.

[e]$44,885,000 unallocated; $55,905,000 unmet.

Table C.6

Number of Assets in Inventory for Selected Cases

Case	Infrastructure	Number of Assets: Depot	PSPs	Bases	Total[b]	Range[b]
Baseline	Standard	26,642	11,168	632	38,442	1,561
	High Velocity	2,605	2,593	404	5,602	948
1992	Standard	10,367	6,966	583	17,916	1,462
Assets	High Velocity	1,892	1,592	379	3,863	883
New PSPs	Standard	27,240	11,857	549	39,646	1,560
	High Velocity	2,653	2,555	288	5,496	936
Single PSP	Standard	21,867	15,351	1,278	38,496	1,560
	High Velocity	2,130	2,670	626	5,426	962
Full Range	Standard	27,012	11,168	632	38,812	1,908
of Parts	High Velocity	3,634	2,593	404	6,631	1,908
All LRUs at	Standard	26,642	11,168	11,857	49,667	1,789
FSLs	High Velocity	2,605	2,593	11,816	17,014	1,400
1994	Standard	16,848	9,156	694	26,698	1,430
Requirement	High Velocity	2,133	1,328	419	3,880	821
Baseline (1992)	Standard	7,610	7,027	666	15,303	
Allocated in 1994	High Velocity	1,185	963	393	2,541	681

[a]The *range* of parts is the number of line items included in the inventory (out of a possible 1,908 line items).

[b]Totals have been rounded.

Table C.7

Mission-Capable (FMC+) Status for Selected Cases (percentage of aircraft PMC+)

Case	Infrastructure	CONUS Main (%)	Guard & Reserve (%)	En Route (%)	Fleetwide (%)
Baseline	Standard	82.3	79.7	11.7	65.9
	High Velocity	83.8	86.2	12.5	68.9
Experienced Factors	Standard	52.5	69.7	7.5	48.4
	High Velocity	79.2	86.5	13.8	67.2
High VTMR	Standard	40.2	55.9	7.5	38.4
	High Velocity	51.9	66.7	15.8	49.0
Surge	Standard	82.6	80.3	12.8	65.8
	High Velocity	82.1	87.3	16.8	68.9
Major Operation	Standard	68.3	42.5	10.8	26.7
	High Velocity	74.2	59.2	14.5	32.3
Transport Cutoff[a]	Standard	80.2	75.4	13.8	63.9
	High Velocity	83.8	83.0	7.9	66.8
FSS Assets Withdrawn	Standard	82.5	80.0	10.0	65.7
	High Velocity	84.2	85.4	15.0	69.4
1992 Assets	Standard	72.1	70.8	7.5	57.4
	High Velocity	82.1	86.0	12.1	68.0
Random Distribution	Standard	81.4	73.3	10.0	62.9
	High Velocity	84.4	76.8	15.8	66.7
New Beddown	Standard	78.3	75.9	14.2	55.0
	High Velocity	80.0	85.6	17.6	59.8
No Improvement	High Velocity	79.2	70.8	5.0	60.0
No Repair Improvement	High Velocity	78.3	72.4	10.0	61.3
1/4 Repair Improvement	High Velocity	80.2	75.7	5.4	62.2
1/2 Repair Improvement	High Velocity	80.2	78.1	9.2	63.9
New PSPs	Standard	83.3	78.7	7.5	65.0
	High Velocity	84.0	86.0	18.0	70.1
Single PSP	Standard	82.7	83.8	10.4	67.2
	High Velocity	80.4	84.3	17.1	67.8
Full Range of Parts	Standard	81.3	78.9	6.7	64.0
	High Velocity	84.4	86.0	17.9	70.3
All LRUs at FSLs	Standard	82.1	78.4	9.2	64.8
	High Velocity	85.0	86.5	18.3	70.8

[a]Performance on day 375, at the end of the cutoff.

Table C.8

Departure Reliability (FMC+ Aircraft) for Selected Cases

Case	Infrastructure	CONUS Main (%)	Guard & Reserve (%)	En Route (%)	Fleetwide (%)
Baseline	Standard	100.0	100.0	19.7	51.6
	High Velocity	100.0	100.0	18.1	50.7
Experienced	Standard	96.4	100.0	12.4	46.0
Factors	High Velocity	100.0	100.0	23.1	53.7
High VTMR	Standard	79.6	90.1	10.5	38.5
	High Velocity	96.9	94.9	20.0	50.5
Surge	Standard	100.0	100.0	19.0	49.1
	High Velocity	100.0	100.0	24.5	52.5
Major	Standard	98.1	87.5	25.0	39.6
Operation	High Velocity	96.3	95.0	33.0	46.0
Transport	Standard	100.0	100.0	19.6	51.6
Cutoff[a]	High Velocity	100.0	100.0	12.8	47.5
FSS Assets	Standard	100.0	100.0	16.5	49.7
Withdrawn	High Velocity	100.0	100.0	22.9	53.6
1992	Standard	100.0	100.0	12.4	47.2
Assets	High Velocity	100.0	100.0	17.5	50.3
Random	Standard	100.0	100.0	17.4	50.3
Distribution	High Velocity	100.0	100.0	22.1	53.1
New Beddown	Standard	100.0	100.0	30.6	58.0
	High Velocity	100.0	100.0	35.3	60.8
No Improvement	High Velocity	100.0	100.0	8.3	44.8
No Repair Improvement	High Velocity	100.0	100.0	17.8	50.5
1/4 Repair Improvement	High Velocity	100.0	100.0	10.3	46.0
1/2 Repair Improvement	High Velocity	100.0	100.0	16.7	49.8
New PSPs	Standard	100.0	100.0	12.7	47.4
	High Velocity	100.0	100.0	25.2	55.%
Single PSP	Standard	100.0	100.0	17.2	50.1
	High Velocity	100.0	100.0	24.2	54.4
Full Range	Standard	100.0	100.0	12.1	47.1
of Parts	High Velocity	100.0	100.0	29.3	57.4
All LRUs at	Standard	100.0	100.0	14.2	48.3
FSLs	High Velocity	100.0	100.0	26.4	55.7

[a]Performance on day 375, at the end of the cutoff.

Table C.9

Pessimistic Issue Effectiveness for Selected Cases (percentage of issues on same day as request for FMC+ aircraft)

Case	Infrastructure	Depot (%)	Shops (%)	Flight Lines (%)
Baseline	Standard	96.9	75.2	18.0
	High Velocity	64.4	47.0	10.3
Experienced Factors	Standard	78.4	68.2	19.4
	High Velocity	45.2	41.1	10.6
High VTMR	Standard	90.3	60.3	12.4
	High Velocity	59.4	32.2	7.4
Surge	Standard	98.1	70.4	20.4
	High Velocity	60.8	41.0	10.7
Major Operation	Standard	89.6	69.0	14.5
	High Velocity	57.1	42.8	9.7
Transport Cutoff[a]	Standard	92.4	55.9	17.0
	High Velocity	53.1	25.5	0.5
FSS Assets Withdrawn	Standard	92.4	71.9	17.1
	High Velocity	67.8	44.3	11.6
1992 Assets	Standard	62.6	56.1	26.6
	High Velocity	63.9	36.4	11.7
Random Distribution	Standard	95.2	66.4	18.8
	High Velocity	63.9	42.2	10.7
New Beddown	Standard	98.1	74.3	23.9
	High Velocity	66.0	49.7	12.5
No Improvement	High Velocity	21.8	38.1	8.2
No Repair Improvement	High Velocity	34.8	41.6	23.1
1/4 Repair Improvement	High Velocity	40.5	39.8	20.9
1/2 Repair Improvement	High Velocity	37.3	48.4	20.3
New PSPs	Standard	96.5	73.1	21.1
	High Velocity	55.9	41.7	11.4
Single PSP	Standard	75.5	91.7	33.4
	High Velocity	42.1	61.9	16.7
Full Range of Parts	Standard	94.6	64.4	15.7
	High Velocity	63.5	44.5	9.6
All LRUs at FSLs	Standard	97.3	71.2	17.5
	High Velocity	62.4	46.3	7.6

[a]Issue effectiveness on day 375, at the end of the cutoff.

Table C.10

Optimistic Issue Effectiveness for Selected Cases (percentage of issues on same day as request for FMC+ aircraft)

Case	Infrastructure	Depot (%)	Shops (%)	Flight Lines (%)
Baseline	Standard	97.0	79.3	57.6
	High Velocity	77.7	59.8	46.1
Experienced Factors	Standard	78.4	69.8	44.1
	High Velocity	51.7	59.0	38.2
High VTMR	Standard	90.9	63.2	38.8
	High Velocity	71.4	41.4	30.0
Surge	Standard	98.2	74.2	58.6
	High Velocity	76.8	54.6	47.2
Major Operation	Standard	89.9	71.1	34.8
	High Velocity	71.4	52.6	30.1
Transport Cutoff[a]	Standard	92.8	59.3	42.1
	High Velocity	56.8	32.1	17.8
FSS Assets Withdrawn	Standard	93.2	76.5	53.9
	High Velocity	80.7	57.1	48.1
1992 Assets	Standard	62.8	58.7	54.5
	High Velocity	73.6	47.9	44.7
Random Distribution	Standard	95.2	70.3	57.9
	High Velocity	77.9	56.7	44.7
New Beddown	Standard	98.2	77.6	57.2
	High Velocity	76.6	59.6	43.6
No Improvement	High Velocity	22.4	40.0	23.4
No Repair Improvement	High Velocity	38.5	44.8	42.1
1/4 Repair Improvement	High Velocity	44.0	45.5	39.9
1/2 Repair Improvement	High Velocity	39.5	55.8	44.9
New PSPs	Standard	96.5	75.4	60.2
	High Velocity	72.2	55.4	44.9
Single PSP	Standard	75.5	94.1	47.0
	High Velocity	58.1	76.5	25.5
Full Range of Parts	Standard	95.2	68.4	55.0
	High Velocity	78.6	59.3	47.7
All LRUs at FSLs	Standard	97.5	74.3	58.0
	High Velocity	76.0	59.2	41.0

[a]Issue effectiveness on day 375, at the end of the cutoff.

Table C.11

Parts Thought to Be "Essential"

FSC	NIIN	Work Unit Code (WUC)	Noun Descriptor
1620	000018416	13BED	actuator; nose landing gear; steering (right hand)
		13FCP	
6610	000180683	51BE0	altimeter; vertical speed indicator
6685	000446034	41JBA	transmitter; manifold; bleed air pressure (A/C
		41JBB	pack)
5831	000523404	64EAB	auxiliary public address control panel
		64EAC	
1650	000600548	14GCS	motor; hydraulic screw drive (S671-3)
1630	000828189	13EED	control box; main landing gear; anti-skid
1650	000984775	11LCD	main landing gear door lock actuator (cylinder)
		13ARE	
		13BDQ	
2915	001117770	23UDE	P & D valve
6685	001136575	41GCH	cabin differential pressure gauge/indicator (altimeter)
1660	001360476	41ABC	valve; temperature condition; upper deck
		41AHH	
		41AJ0	cargo compartment temperature control box
		41CCH	valve; F/S, R/C, T/C, U/F; temperature
4320	001521488	45ABC	suction boost pump; electric
		45AEC	
1680	001851139	13BEE	nose landing gear door brake
1560	002202882	14LAX	#1 moving island nose door (panel assembly)
6615	002321544	14AJB	aileron actuator
4320	002421043	23VAE	lube, oil, and scavenge pump
1680	002487638	14JDJ	flap torque limiter; 4B, 5B (left)
6610	002499447	13GE9	indicator; main landing gear position (left hand)
		13GEA	
1680	002679990	13GB0	actuator; kneel pad
		13JAB	
		13JAD	
		13TEV	
		13AQL	main landing gear/nose landing gear door lock
		13ARA	control valve
		13ARE	
		13ARU	
		13ASM	
		13BME	
		13GCM	
6615	004169660	14EGL	actuator assembly; outboard elevator
		14EGQ	

Table C.11—continued

FSC	NIIN	Work Unit Code (WUC)	Noun Descriptor
5826	004606693	66AB0	CDPIR electronics unit
		66AE0	
		66AG0	
4820	004492840	13ECC	metering valve; brk pilot
6625	004713174	65ACB	test set transponder
1660	004854061	41AC0	control box; floor heat
		41CA0	
1650	004866297	45JAL	PTU motor (hydraulic) assembly (SOV suction
		45JJA	ATM)
1650	004877678	11BCA	main landing gear motor
1650	004884605	13AQG	cartridge; valve (DCE-12)
1650	005350662	14AJC	aileron manifold (valve)
		45AJ9	
		49BBM	
6615	005370580	52JC0	flight augmentation panel
6605	005600303	51AFA	indicator; horizontal; suit
1660	006888451	41VDE	side (main) windshield control box; heat
4320	007264435	45LAG	ATM hydraulic pump
		45LAS	
1650	007282780	24ALA	APU (GTU) hydraulic start motor
1660	007524980	41VDF	side (main) windshield control box, heat
			(transformer rectifier unit)
4810	007604136	41GCB	valve; pylon bleed air shut off
2995	007612851	23EAK	valve; control; engine starter
6680	007718158	45PAA	hydraulic quantity indicator
6610	007826892	51BGE	true A/S indicator
6685	008091394	51BGC	indicator; total temperature
1680	008333945	14NHM	actuator; lockout ground spoiler
		23ZKK	
6620	008344265	23XHF	fuel flow transmitter
5945	008561797	42JAG	APU and external power contactor
6615	008577312	52AJJ	aileron/elevator cable position transducer
		52JDA	
1650	009322708	11BCY	visor cable lock actuator
6615	010079130	52AEA	servo assembly A/P elevator (pitch/roll)
		52AJA	
5826	010121938	71BA0	TACAN receiver/transmitter
6605	010182181	72HA0	inertial navigation system unit
6605	010352009	72H99	inertial navigation system control display unit
		72HB0	
5930	010428750	42EAJ	switch; underspec; pressure; oil
		42EAM	
5820	010621019	62BA0	transceiver VHF (receiver/transmitter 1300)
		62EA0	

Table C.11—continued

FSC	NIIN	Work Unit Code (WUC)	Noun Descriptor
5985	010890737	72AC0	antenna; AS-3440
5841	010891064	72AB0	radar scope; indicator (IP 1374)
2915	010914813	23UAE 23VAE	main fuel pump
5841	010918929	72AA0	weather radar; receiver/transmitter (1338)
6680	011016436	45JAL 46GAC 46GAD 46GAE	indicator; fuel quantity (#1 or 4 auxiliary)
6680	011016438	45GAB 45JAL 46AAG 46GAB	indicator; fuel quantity (#2 or 3 main)
5821	011136476	62DA0	ARC-186 dual control box (panel); VHF
6610	011307057	66GA0	digital flight data recorder
6610	011326661	51CC9	FSAS computer (GPWS comparator [mark II])
6610	011440719	51CB0	display interface control unit; FSAS
1560	011492746	11WFZ	nose radome assembly
6620	011569724	46ECB	fuel pressure transmitter
6680	011609435	46GAG 46GCB	totalizer; digital
1650	011611651	42EAB	constant speed drive
1680	011612102	14JEJ	right flap actuator (C5A)
6110	011626490	42JAQ	bus protect panel; ac power (C5B) (turbine air cooling)
6110	011650240	42EAR 42EAS	load controller (CSD; C5B)
1680	011815647	14LDG	slat actuator (C5A)
6615	011877821	52PA0	ALDCS computer
1630	011897830	13DAB	deflation valve
5998	011908296	55CNC 55CNG 55CNH	SAR #4 (C5B)
5895	011925440	64AC0 64AD0	control indicator panel (INPH)
5826	011945731	71CAA	ADF receiver
1620	012050901	13AAA	strut; main landing gear; aft
5985	012058599	16BC0	ARC-190 coupler
4810	012110166	23SAF	valve, anti-icing
2915	012147308	23UAJ 23UDE	fuel control
1650	012173659	13GCB	valve; main landing gear door; lock/unlock
6610	012262152	51CA0	control display unit; FSAS

Table C.11—continued

FSC	NIIN	Work Unit Code (WUC)	Noun Descriptor
6340	012285939	49ACD 49ADB	control; engine/APU fire
5841	012316437	72FB0	indicator; ALT CARA (APN-232)
6615	012477293	52JB0	pitch augmentor computer (C5B)
4920	012521095	55CNG	SAR 14 (MADAR II)
6685	012767803	23XDA	indicator, TIT
5821	012866543	61BA0	receiver/transmitter (1341) (ARC-190)
1650	013044171	45AGB	engine dual hydraulic filter assembly
1660	013079561	41AWF	turbine (C5B)
6610	998919991	51BB0 51BK0	computer (SCADC)

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